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THE GRANITE, PEGMATITE, AND REPLACEMENT VEINS IN THE SHEAHAN QUARRY, GRANITEVILLE, MISSOURI*

CARL TOLMAN AND SAMUEL S. GOLDICH,
Washington University, St. Louis, Mo.

INTRODUCTION

Graniteville, Iron County, Missouri, has been for some time the most important granite quarrying center in the state. The Sheahan quarry located just north of Graniteville village is at present the most active one in the district. The quarry product is the distinctive "Missouri red granite" of pre-Cambrian age. The granite, a pegmatite, and replacement veins exposed in the quarry afforded material for a petrographic and chemical study presented in this paper.

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GRANITE

Feldspar and quartz make up 96 to 97 per cent of the granite. The feldspar includes two generations of albite, orthoclase and microcline. Both orthoclase and microcline are intergrown with albite forming several types of perthite. Microcline-albite intergrowths are usually of the type described by Andersen[1] as "vein" perthite. The orthoclase-albite intergrowths are much less regular and are of the "patch" type. A third perthitic development is "poikilitic"; allotriomorphic to hypidiomorphic crystals of albite are included in larger crystals of vein and patch perthite.

The earliest feldspar of the granite is an albite near oligoclase which occurs in crystals up to an inch or more in length. Albite also appears to be the last feldspar, a second generation of this

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[1] Andersen, Olaf, *Norsk. Geol. tidsskrift*, vol. **10**, pp. 116–203, 1928.

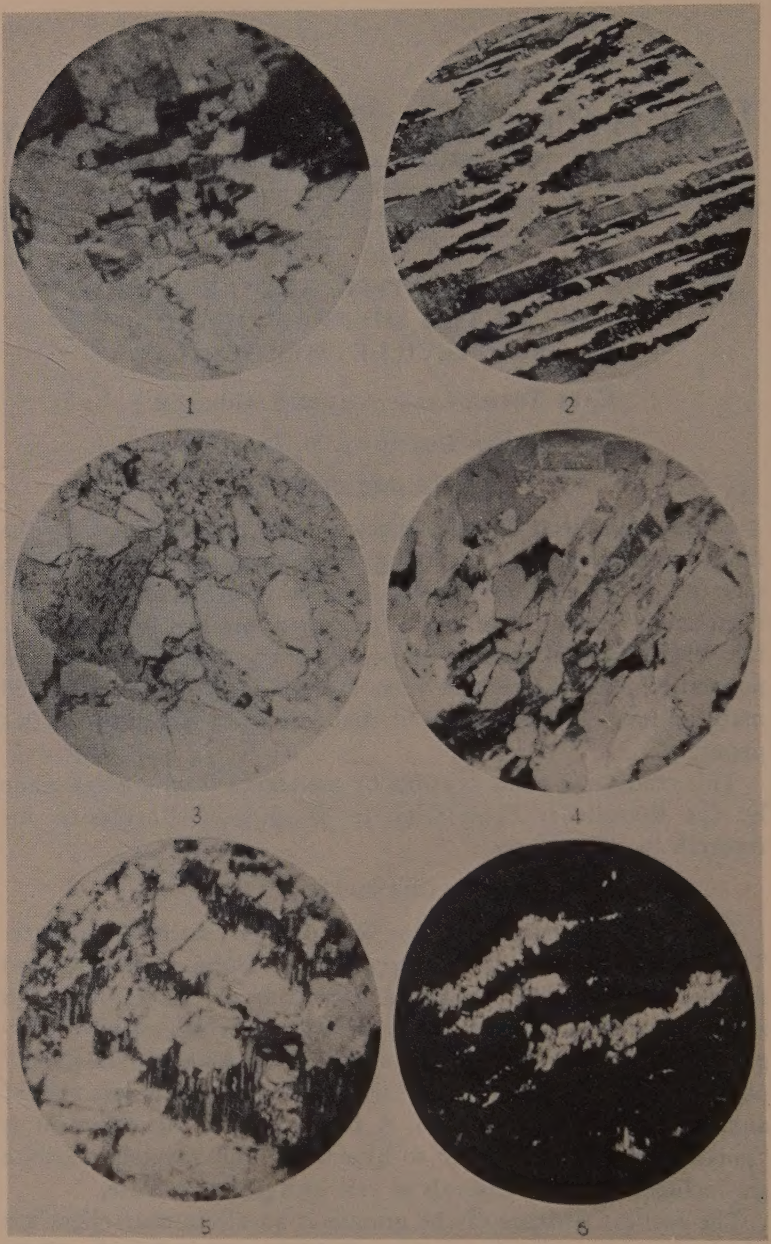

FIG. 1. Sheahan quarry granite. The late "blocky" albite is shown. Crossed nicols. ×43; fig. 2. Perthite of the vein type from the pegmatite. Crossed nicols. ×38; fig. 3. Topaz (light) replaced by beryl (dark). Crossed nicols. ×43; fig. 4. Topaz replaced by muscovite. Crossed nicols. ×43; fig. 5. Topaz and muscovite replaced by albite. Crossed nicols. ×43; fig. 6. Feldspar (light) replaced by fluorite (dark). Crossed nicols. ×43.

mineral occurring in small unaltered grains interstitial to the larger minerals and sometimes as a "blocky" fringe bordering earlier feldspar (Fig. 1). Other minerals, some of which are secondary products, include apatite, biotite, calcite, chlorite, fluorite, hematite, leucoxene, magnetite, muscovite, pyrite, sericite, and zircon. Apatite is very rare, and only a few scattered crystals were noted. Biotite is not common and has been largely altered to "green-biotite" and chlorite. A few grains of zircon with characteristic haloes are found as inclusions in the biotite.

Magnetite is of interest because it occurs both as an early and as a late mineral. In the second occurrence it is usually associated with muscovite which replaces feldspar and to a lesser extent quartz. It is possible that the muscovite is deuteric and was derived from an earlier iron-bearing mineral such as biotite by the action of late magmatic juices. Such a reaction might produce a mica more closely allied to muscovite at the same time liberating iron which became fixed as magnetite. The muscovite is colorless or has a faint olive-green to colorless absorption. It is probably a closely related if not the same mica which occurs abundantly in the pegmatite and veins.

Although pyrite was not observed in thin sections prepared from chips taken from the material used for chemical analysis, this mineral is present in the granite near joint planes. The chlorite apparently derived from biotite is blue-green in color and is characterized by blue-grey interference colors. 2V is small and negative, and the mineral is probably negative-penninite or delessite.

CHEMICAL ANALYSIS

A chemical analysis was made of a sample prepared from several pounds of chips representing the massive granite. The results of the analysis and the calculated normative minerals are shown in Table 1. Normative albite exceeds normative orthoclase, a feature in keeping with the usual high soda content of the acid igneous rocks of the St. Francois Mountains. Phosphorus and other minor constituents were found only in small amounts.

PEGMATITE

Abnormally large developments of quartz and feldspar which locally result in pegmatitic granite can be observed in a number of places in the Sheahan quarry. Recently, however, a lens of peg-

TABLE I

Chemical analysis and classification of Missouri red granite from Sheahan quarry, Graniteville, Missouri. S. S. Goldich, analyst.

	Per cent	*Mol. No.*
SiO_2	76.81	1.280
Al_2O_3	12.23	.120
Fe_2O_3	0.52	.003
FeO	0.41	.006
MgO	0.12	.003
CaO	0.98	.018
Na_2O	3.85	.062
K_2O	4.59	.049
H_2O+	0.26	
H_2O-	0.01	
CO_2	0.07	.0016
TiO_2	0.08	.001
ZrO_2	0.02	.0003
P_2O_5	Trace	
S	0.01	
Cr_2O_3	0.00	
MnO	0.00 (.004)	
BaO	0.01	
F	0.17	.0045
	100.14	
Less O	.07	
	100.07	

Norm	
Quartz	35.14
Zircon	0.05
Orthoclase	27.24
Albite	32.49
Anorthite	2.50
Diopside	1.14
Magnetite	0.70
Ilmenite	0.15
Fluorite	0.35
Calcite	0.16
	99.92

Specific gravity 26°/4° = 2.607
Class I, Subclass 1, Order 4, Rang 1, Subrang, 3.
Rock name: LIPAROSE.

matite distinctive in its mineral assemblage was discovered. The pegmatite is exposed on the upper bench of the north face of the quarry near its western end. The outcrop is about 10 feet in length and has a maximum thickness of about 18 inches. Though it appears to be roughly lens-shaped, the pegmatite thins and swells irregularly. The strike is parallel to the prominent joint system of the quarry (N. 65° E.), and the dip is about 60 degrees to the northwest.

Large blocks of pegmatite found on the quarry floor below the outcrop indicate that considerable material may have been removed in the quarrying operations. However, because of the steepness of the dip, any portion of the pegmatite continuous with the outcrop would have been truncated within a short distance by the present erosion surface.

MINERALOGY

Most of the pegmatite in the outcrop is composed of feldspar and quartz. Topaz, mica, fluorite, and a few other minerals are present, but of special interest is beryl, a mineral hitherto not described in any Missouri occurrence.

PERTHITE. An intergrowth of massive quartz and feldspar represents the early or magmatic phase of the pegmatite. The feldspar which attains a maximum length of 8 inches is a perthitic intergrowth of microcline and albite of the "vein" type (Fig. 2). The mineral is red in color, and in thin section a small amount of finely dispersed hematite is visible. An analysis by Goldich gave the following results:

SiO_2	65.85
Al_2O_3	18.85
Fe_2O_3	0.11
FeO	Trace
MgO	0.00
CaO	0.05
Na_2O	3.91
K_2O	11.15
H_2O+	0.24
H_2O-	0.01
	100.17

Specific gravity 26°/4° = 2.553

The analysis of the perthite calculated into feldspar molecules gave the following percentages:

K-feldspar	65.6
Na-feldspar	33.0
Ca-feldspar	0.3

TOPAZ. The topaz is colorless or light yellow with a vitreous luster. It occurs in coarsely granular aggregates, and crystal faces are rare. Topaz is always in close association with beryl and muscovite, and replacement by these minerals (Figs. 3 and 4) and by albite (Fig. 5) is so general that the original relationships of the topaz could not be determined. Topaz is considered to be the earliest hydrothermal mineral.

BERYL. Massive beryl is common, but there is a greater tendency for this mineral to develop crystal forms than is true of the topaz. Hexagonal prisms two inches in length were found. The beryl varies from colorless or a faint blue to a fine aquamarine color, but none is of good gem quality. Indices of refraction are: $\epsilon = 1.571 \pm .002$; $\omega = 1.578 \pm .002$.

The best material was carefully selected for chemical analysis by hand picking. The mineral was crushed and sieved to a uniform size (1/4 to 1/8 mm.), and was separated from topaz with which it is intimately associated by means of bromoform (specific gravity, 2.83). The beryl was recovered as the float fraction and after being washed and dried was further cleaned by hand picking under a binocular microscope. The chemical analysis of this material by Goldich follows:

SiO_2	65.23
Al_2O_3	17.99
Fe_2O_3	0.96
FeO	0.57
BeO	13.39
MgO	0.06
CaO	0.03
Na_2O	0.52
K_2O	0.01
H_2O (Ignition)	1.20
H_2O-	0.03
	99.99

Specific gravity 24°/4° = 2.682

Beryllium was separated from aluminum and iron by 8-hydroxyquinoline.[2] Total iron was determined on a separate portion by fusing the sample with sodium carbonate, dissolving the melt in HCl and determining the iron by potentiometric titration with dichromate following reduction with stannous chloride. Alumina was then obtained by difference. Incipient alteration of the beryl to a clay-like substance was observed, and this may be a hydrated secondary product contributing to the observed loss on ignition. The beryl is also replaced by a dark-green mica which has been oxidized to a yellowish to reddish oxide of iron, probably goethite, and this mineral likewise may account for some of the water as well as for part of the ferric iron.

[2] Kolthoff, I. M., and Sandell, E. B., *J. Am. Chem. Soc.*, vol. **50**, p. 1900, 1928.

The beryl is of the low alkali type, the specific gravity and optical data being in accord with the chemical data. Beryl replaces topaz and feldspar (Fig. 3) and is replaced chiefly by mica.

ALBITE. Albitization affected both the granite and the pegmatite and possibly the late albite of the rock is related to that which replaces the perthite, quartz, topaz and early muscovite of the pegmatite. The perthite, itself, may represent an early (deuteric) replacement of massive microcline.

The albite is pink to deep red in color and in thin section is characterized by sharply defined twinning lamellae which are not continuous but broken to give a patch-like appearance between crossed nicols.

Albite is also found in veinlets one to two millimeters in width. This albite is somewhat unusual because of the absence of prominent twinning. Powdered material showed the composition to be near $Ab_{95}An_5$. Extinction on the basal pinacoid, X to (010), is 3–4 degrees. Indices of refraction are: $\alpha=1.529$; $\beta=1.533$; $\gamma=1.539$; all $\pm .002$.

BIOTITE. A number of micas are present in the pegmatite. An early mica is dark-green in color and is strongly pleochroic, dark green to light greenish-yellow. 2V is small, 10° or less, and the mineral is optically negative. The birefringence is high and is about that of the normal brown biotite.

MUSCOVITE. The most abundant mica in the Sheahan quarry is an iron-bearing muscovite which varies in color from light yellowish-brown to almost black. Optical properties also vary, and these variations are probably controlled by the tenor of ferrous and ferric iron. Only the light brown mica which is found in booklets measuring an inch or more in diameter was studied in any detail. Dr. Ellestad of the Laboratory for Rock Analysis at the University of Minnesota determined the alkalies on this muscovite. Chemical data are shown in Table II. The combined figures of the partial analyses yield a total of 98.69 per cent. The low summation may be due to the presence of fluorine which was not determined or to an error in the figures for water. The hydroxyl was therefore omitted in the calculation of molecules. The analysis gives a $K_2O:SiO_2$ ratio of 1:6 making it necessary to use Hallimond's[3] formula for phengite ($K_2O.2Al_2O_3.RO.6SiO_2.2H_2O$)

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[3] Hallimond, A. F., On the chemical classification of the mica group: *Mineral. Mag.*, vol. **XX,** pp. 305–318, 1925.

rather than the one suggested by Winchell[4] ($K_2O.2Al_2O_3.RO.7SiO_2.2H_2O$). The calculated molecules are

Phengite	52.4%
Fe''' Muscovite	19.7
Muscovite	26.4
	98.5

Beta was found to be 1.596 ± .002; 2V is about 30°. The optical data agree fairly well with the position a muscovite of the above composition would have on Winchell's diagram except that 2V is too small. The diagram, however, is based on data for phengite high in MgO, and according to Winchell,[5] ferrous iron is more effective in reducing the optic angle than is magnesia.

TABLE II

Chemical data on muscovite occurring in large books in pegmatite and veins in the Sheahan quarry.

	1	2	*Mol. No.*		*Ratios*
SiO_2	45.92		.763	.768	6.00
TiO_2	0.36		.005		
Al_2O_3	29.07		.285	.380	2.97
Fe_2O_3	3.94		.024		
FeO	3.58		.050		
MnO	0.06		.001		
MgO	0.79		.020		
CaO	Trace				
Li_2O	n.d.	0.29	.010	.128	1.00
Na_2O	n.d.	0.27	.005		
K_2O	n.d.	10.68	.113		
H_2O above 110°C.	3.20			.207	1.62
H_2O below 110°C.	0.53				
F	n.d.				

1. S. S. Goldich, Analyst.
2. R. B. Ellestad, Analyst.

SERICITE. Felted aggregates of sericite compose greenish masses which in hand specimens have an appearance like that of serpentine. The sericite seems to be later than the muscovite and in part replaces it.

FLUORITE. Fluorite is abundant in the pegmatite and replaces feldspar, mica, and beryl. The replacement of feldspar by fluorite and likewise by beryl resulted in a structure in which stringers of albite are found as remnants in the invading mineral (Fig. 6). These elongated residuals of albite may have resulted from a selective replacement of perthite.

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[4] Winchell, A. N., Further studies in the mica group: *Am. Mineral.*, vol. **XII**, pp. 267–279, 1927.

[5] *Op. cit.*, p. 269.

OTHER MINERALS. Rutile and cassiterite were noted in a few thin sections of pegmatite minerals. Only a few small crystals were found, and their position in the mineral sequence could not be determined. Magnetite, specularite, and pyrite occur in scattered grains. Polished sections showed some of the pyrite is replaced by chalcopyrite which is in turn replaced by galena.

REPLACEMENT VEINS

A number of quartz veins are present in the north face of the Sheahan quarry. These veins have the same general strike as the joints, but some differ in dip. The largest observed is four inches in width. The veins are of a replacement nature, and the walls are often indefinite. Fragments of granite in all stages of replacement are included. Quartz in terminated crystals and thuringite were found in vugs.

The granite wall rock in many places along the quartz veins has been mineralized with magnetite. Octahedrons of magnetite two millimeters in size also occur in the quartz. Some pyrite is present.

JOINT-VEINLETS

Secondary minerals, the most prevalent of which are muscovite, fluorite, and pyrite, have been developed rather generally along the joint planes. In most places these minerals represent a thin film replacing the granite, but locally these replacements are several inches in thickness.

PARAGENESIS

The pegmatite is of the complex type with both magmatic and hydrothermal stages present. The first stage is represented by the coarse feldspar and quartz. The development of these minerals was undoubtedly influenced by the presence of mineralizers. As these mineralizers became concentrated as a consequence of crystallization, the magmatic stage gave way to a hydrothermal stage.

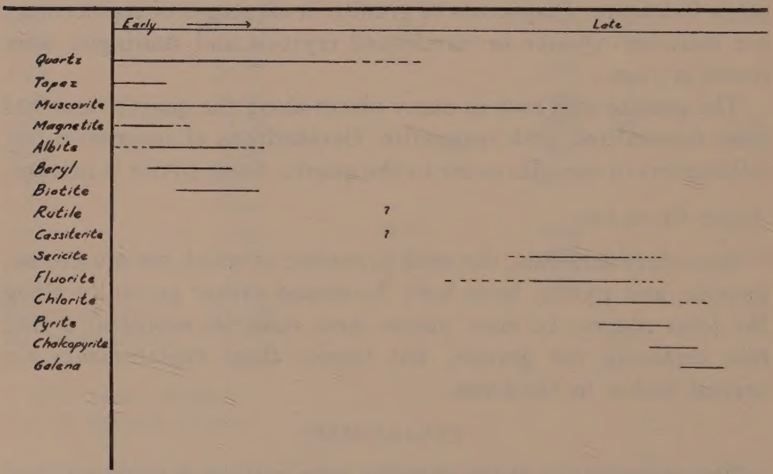
The hydrothermal stage of the pegmatite is marked by the deposition of a series of minerals, by progressive replacement of early minerals by later ones. The hydrothermal minerals in the order of their development as determined from replacement relationships shown in thin sections are topaz, muscovite, beryl and albite, biotite, muscovite, rutile and cassiterite (?), sericite and fluorite, pyrite, chalcopyrite, and galena.

Throughout the granite mass deuteric and hydrothermal activity resulted in albitization and replacement of feldspar and quartz by magnetite, muscovite, fluorite and other secondary minerals. Hydrothermal solutions in their ascent became more or less restricted to channels and developed the quartz veins and the joint-veinlets described.

The paragenesis of the hydrothermal minerals found in the pegmatite and veins in the Sheahan quarry is shown in a generalized manner in Table III.

TABLE III

Relative Age of Hydrothermal Minerals in Pegmatite and Veins



SUMMARY AND CONCLUSIONS

1. Granite, pegmatite, and replacement veins in the Sheahan quarry, Graniteville, Missouri, are genetically related.

2. The granite is composed of quartz, albite, orthoclase, microcline, and a small amount of accessory minerals. The feldspar shows much perthitic intergrowth and some late albitization. Secondary minerals include magnetite, muscovite, fluorite, sericite, chlorite, calcite, hematite, and pyrite.

3. The pegmatite is of the complex type. Perthite and quartz represent the magmatic stage. The hydrothermal minerals are topaz, muscovite, albite, beryl, biotite, rutile, cassiterite, sericite, fluorite, pyrite, chalcopyrite, and galena.

4. Quartz, magnetite, muscovite, fluorite, specularite, pyrite, and chlorite are found in replacement veins and in joint-veinlets.

5. Chemical data for the granite, perthite, beryl, and muscovite are given. Optical data for the minerals are also included.

6. The Sheahan quarry pegmatite is the only complex pegmatite so far encountered in the St. Francois Mountains.

ALTERATION OF THE LAVAS SURROUNDING THE HOT SPRINGS IN LASSEN VOLCANIC NATIONAL PARK

Charles A. Anderson, *University of California, Berkeley, Calif.*

INTRODUCTION

The general characters and many important details regarding the hot springs of the Lassen Volcanic National Park, California, have been presented by Day and Allen[1] in their admirable treatise. In this work, they devoted some discussion to the character of the rock decomposition produced by the hot springs, but indicated that further studies might profitably be made. Mr. R. H. Finch of the U. S. Geological Survey Volcanological Observatory, Mineral, California, also suggested the desirability of this work and to him the writer is indebted for many courtesies during the pursuit of the field work. It is a pleasure to acknowledge the helpful comments of Dr. E. T. Allen of the Geophysical Laboratory, Washington, D. C., regarding the character of the lava alterations.

The writer wishes to express his thanks to the members of the Board of Research of the University of California for the award of a grant used for the preparation of thin sections and chemical analyses.

Dr. Howel Williams made some observations on the decomposition of the lavas while studying the geology of the region and has incorporated this information in his excellent report. For the location and geologic environment of the hot springs, the reader is referred to his map.[2]

Four main groups of hot springs were visited, Boiling Lake, Devil's Kitchen, Bumpass Hell, and Supan's Springs (Tophet Springs on the U. S. G. S. map). These lie southeast to southwest of Lassen Peak. Detailed maps of the first three areas showing the location of the various springs are to be found in the report of Day and Allen.[3]

ALTERATION OF THE LAVAS

Source and Nature of Acid. According to Day and Allen, the chief agent responsible for the alteration of the lavas is sulphuric acid. In their discussion of the origin of this acid, they concluded that it formed in part from the direct oxidation of hydrogen sulphide under the conditions prevailing in the hot spring basins. Also deposition of free sulphur and later oxidation in the moist warm air might form additional sulphuric acid.[4] According to them "none of the waters of these hot springs is far from neutrality. Of those analyzed six were practically neutral, four were alkaline and eight were acid. The acidity ranged from 19 mg. to 436 mg. H_2SO_4 per liter, that is, from 0.002 to a trifle over 0.04 weight per cent."[5]

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[1] Day, Arthur L., and Allen, E. T., The volcanic activity and hot springs of Lassen Peak: *Carnegie Inst. Wash. Publ.* **360**, 1925.

[2] Williams, Howel, Geology of the Lassen Volcanic National Park, California: *Bull. Univ. of Calif. Publ., Dept. Geol. Sci.*, vol. **21**, pp. 195–385, 1932.

[3] *Op. cit.*, pp. 92, 95 and 114.

FIELD APPEARANCE. Several rock types have been affected by the action of the hot springs. These range from blue-black basalts at Boiling Lake, gray pyroxene andesites at Devil's Kitchen and Supan's Springs, to pale gray dacites at Bumpass Hell. Regardless of the initial character of the rock, they have been bleached and decomposed to glaring white, rarely to yellow brown and red products. Among these decomposed lavas lie clusters of fumaroles, hot springs and mud pots, containing sediments of decomposed lavas.

MINERALOGICAL CHARACTER. It is generally assumed that lavas attacked by sulphuric acid will alter to opal with the liberation of the alkalies, alkaline earths, iron, and aluminum as soluble sulphates. Although various soluble sulphates of these bases do occur around the hot springs, the insoluble residue does not in all cases consist of pure opal, for muds from the hot springs may be composed of nearly pure kaolin while others consist of opal and kaolin in varying ratios.

Opal. The opal is usually white and powdery; locally it may be compacted, and have waxy fracture surfaces. When examined under the microscope, it appears in honey yellow and dark gray grains, the latter evidently developing from the ferromagnesian minerals. The index of refraction is variable, chiefly ranging about $1.450 \pm .005$, but values as low as $1.410 \pm .003$ were observed.

Kaolin. Frequently this mineral is so intimately associated with opal that no reliable value of the refractive indices can be obtained. Microcrystalline aggregates usually have an index of $1.565 \pm .005$ but owing to the absence of large crystals, the interference colors are hardly perceptible. Some isotropic aggregates gave very low values for the index of refraction ($n=1.52\pm.10$) suggesting halloysite. Four powder x-ray patterns of kaolin-rich sediment were prepared through the kindness of Mr. W. H. Dore, of the Division of Plant Nutrition, University of California, and these were examined by Professor Adolf Pabst of the department of geology of the same University. Owing to the contamination by alunite, quartz and tridymite, the several kaolin minerals could not be distinguished.

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[4] For the evidence pointing to this conclusion see Day and Allen, *op. cit.*, pp. 138–140.

[5] *Op. cit.*, p. 113.

Alunite. Alunite ($K_2O \cdot 3Al_2O_3 \cdot 4SO_4 \cdot 6H_2O$) is almost ubiquitous. This mineral is easily recognized because of its higher indices of refraction and greater birefringence compared to the common associates. It is present in isolated crystals and aggregates, the crystals seldom exceeding .03 mm. in dimension.

Tridymite. The tridymite may be residual in part, but is largely secondary. It occurs in radiating twinned crystals, .1 to .2 mm. in length, usually associated with opal or chalcedony. The optical properties are $\alpha=1.474\pm.002$; $\gamma=1.478\pm.002$, parallel extinction with negative elongation, $2V=30°–40°$ (estimate), positive. A thin section was treated with fuchsine dye after a 20 minute treatment with concentrated hydrochloric acid in order to eliminate the possibility that the tridymite might have been confused with a zeolite. The mineral remained unstained.

In addition to these minerals, quartz is occasionally found, residual in part. Pyrite is common in the sediments of the mud pots, though rarely found in the decomposed lavas surrounding the hot springs. Residual minerals include plagioclase, pyroxene, and to a minor extent, hornblende, biotite and magnetite. Zircon is present in many samples; and has probably been concentrated in some of the mud pots.

STAGES IN DECOMPOSITION. In many places it is possible to find fragments of lavas that have been partly altered so that a core of the original rock remains. At Devil's Kitchen and Bumpass Hell talus material is gradually brought to the hot springs, while at Supan's the hot springs occur in a caldera where the fragmental rocks suggest agglomerates and breccias infilling a vent.[6] Without exception, the soft, white, chalky exteriors are composed largely of opal with minor amounts of alunite. In a few specimens, tridymite was found, and, to judge from chemical analyses and staining with fuchsine dye, kaolin is also present in minor amounts.

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[6] Williams, *op. cit.*, p. 244.

Williams[7] has suggested that decomposition commences with the porphyritic pyroxenes, for specimens studied by him from the western end of Bumpass Hell and from Diamond Peak showing incipient alteration are characterized by chlorite, calcite, (?) sericite and talc pseudomorphs of the ferromagnesian minerals. However, among the specimens studied by the writer in which blocks of lava with a decomposed exterior grade to a fresh core, this selective decomposition is not apparent. In some specimens there may be limited selection of the feldspar phenocrysts while in others the groundmass has suffered more alteration. Locally the boundary between fresh and decomposed rock is quite sharp, but elsewhere it is feathery. Again, a hard bleached zone an inch or more in width separated the two. But no early decomposition of the ferromagnesian minerals is discernible and in some partially altered lavas, fresh pyroxene is imbedded in opal. The cause of these conflicting observations may be that the specimens studied by the writer represent fragments of lavas that are being altered at the present time, while the specimens studied by Williams are now removed from active solfataric action and may be the result of decomposition when the solfataric action was of a different character.

Frequently there is a retention of the original texture even after complete alteration. In thin section the outline of the phenocrysts and microlites will be well preserved and the original ferromagnesian minerals will be marked by opal colored with dark dust. But when the polarizer is inserted, the field appears black owing to the isotropic opal with the exception of occasional tridymite and almost ubiquitous alunite crystals. The latter mineral may be found concentrated near the fresh rock replacing the plagioclase or scattered evenly throughout the altered rock. A surprising feature is the presence of original magnetite crystals in some of these intensely decomposed lavas; evidently the magnetite is not appreciably attacked by the sulphuric acid.

Bumpass Hell. A sample of dacite from Bumpass Hell (spring 14) was selected for analysis of the core, bleached hard transition zone, and the soft powdery exterior (Table I, nos. 1, 2, 3). Some alteration of the core has taken place judging from the rather high content of water, although no perceptible alteration is visible in thin section. The progressive leaching of the bases outward from the core with marked increase in the silica content is quite pronounced. In the transition zone, a striking feature is the relatively high amount of sulphate. Assuming that the K_2O and Na_2O are combined in alunite, there should be 9 per cent of alunite in this zone, with only 1 per cent in the altered exterior. The analysis indicates that the altered material is largely opal, and this is easily confirmed under the microscope. In addition scattered residual quartz phenocrysts from the original dacite add to the content of silica. Tridymite is present in minute wedge-twinned crystals, in part associated with chalcedony. From the analysis, it is seen that only a fraction of the alumina is present in alunite, and assuming that all of it is combined to form kaolin there would be 2½ per cent of this mineral in the altered exterior. Upon staining a slide with

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[7] *Op. cit.*, p. 263.

Table I

	1	2	3	4	5	6
SiO_2	63.80	75.70	92.20	57.25	47.51	54.97
TiO_2	0.55	0.65	1.25	0.42	0.65	0.83
Al_2O_3	17.55	8.53	1.02	18.25	34.08	27.72
Fe_2O_3	1.28	1.85	nil	1.44	1.17	0.88
FeO	2.44	1.40	0.40	4.73	0.52	0.32
MgO	2.02	0.05	nil	4.57	0.28	0.20
CaO	2.60	0.50	0.35	8.12	0.08	0.39
Na_2O	2.70	0.12	tr	2.85	0.21	0.41
K_2O	1.82	0.89	tr	0.99	0.11	0.46
H_2O+	2.80	3.42	1.65	0.65	11.60	9.93
H_2O-	1.85	2.40	2.80	0.31	1.89	2.54
CO_2	nil	nil	nil	—	—	—
ZrO_2	—	—	—	0.01	0.09	0.03
P_2O_5	tr	tr	nil	0.18	0.81	0.11
MnO	tr	nil	nil	0.11	tr	—
S		0.05	0.03	—	0.63	1.11
SO_3	0.48	4.58	0.35	—	—	—
BaO				0.05	0.05	0.03
SrO				0.08		
	99.89	100.14	100.05	100.01	99.68	99.93

1. Fresh core dacite block, Bumpass Hell
2. Bleached transition zone
3. White powdery exterior

Analyses by W. H. Herdsman.

4. Basalt from Boiling Lake
5. Mud from Boiling Lake
6. Mud from Devil's Kitchen

Quoted from Williams, *op. cit.*, p. 285. Analyst, Wheeler.

fuchsine dye, and assuming that the finely divided material that absorbed the dye is kaolin,[8] it appears that the mineral is largely developed in some of the phenocrysts and microlites of feldspar, in intimate association with opal. This mixture is sensibly isotropic and no reliable value of the index of refraction can be obtained.

Some tridymite is present in the glassy groundmass of the unaltered core and may be original similar to the occurrences reported by Kuno.[9] But much tridymite is associated with veinlets of pyrite and chalcedony, and must therefore be of secondary origin. Also it is usually concentrated in the completely altered exterior, so that it appears to be forming now. This is of interest because the temperatures of this spring are recorded by Day and Allen[10] as ranging from 90°C. to 94.1°C. the latter being above boiling point at that elevation. Daubrée[11] has reported the formation of tridymite at temperatures as low as 73°C. at Plombières, France, where Roman bricks have been altered by hot spring action to a zeolitic mass containing opal and tridymite.

Table II

Partial Analyses

	1	2	3	4	5	6	7	8	9	10
SiO_2	93.6	58.2	60.5	60.1	98.3	63.7	70.5	71.9	90.5	94.79
Al_2O_3	3.0	26.2	23.3	28.7	1.5	20.4	17.8	20.2	1.6	1.18
Loss on ignition	3.7	16.0	15.2	11.2	0.6	15.9	11.5	8.1	8.3	3.05*

* Reported as H_2O.

1. Specimen immersed in hot water, Devil's Kitchen.
2. White sediment from hot spring fifty feet above Warner Creek, Devil's Kitchen.
3. Mud from mud pot above Warner Creek, Devil's Kitchen.
4. Sediment from mud pot near water level of Warner Creek, Devil's Kitchen.
5. Dense white altered lava, not near present activity, Supan's Spring.
6. Sediment from mud pot, north of highway, Supan's Spring.
7. Sediment from mud pot, Bumpass Hell.
8. White altered lava along road cut, Little Hot Spring Valley.
9. Near No. 8.
10. Sample from surface of hill, Bumpass Hell. Quoted from Day and Allen, *op. cit.*, p. 142.

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[8] Holmes, Arthur, *Petrographic methods and calculations*, p. 275, **1931**.

[9] Kuno, Hisashi, On silica minerals occurring in the groundmass of common Japanese volcanic rocks: *Bull. Earthquake Research Inst., Tokyo Imp. Univ.*, vol. **11**, pp. 382–390, 1933.

[10] *Op. cit.*, p. 107.

[11] Daubrée, M., Sur la présence de la Tridymite dans les briques zéolithique de Plombières: *Bull. Geol. Soc. France*, 3rd ser., vol. **4**, pp. 523–524, 1876.

DEVIL'S KITCHEN. The soft powdery exterior of a block of andesite partly submerged in the hot water of spring 1, Devil's Kitchen, was partially analyzed (Table II, No. 1) and is practically identical with the analyzed material from Bumpass Hell, except for a higher content of alumina. If all of this alumina is present in kaolin, there would be over 7 per cent of this mineral in the decomposed lava, but actually the amount is less due to the presence of alunite. Staining with fuchsine dye revealed that the clay is limited to original feldspar microlites, and as in the specimen described from Bumpass Hell the clay is intimately admixed with opal. Tridymite is also present in wedge-shaped twins. A veinlet of opal containing crystals of alunite indicates that this mineral may be deposited from solution.

Two samples of andesite were studied from Devil's Kitchen where only steam now has access to the rocks; here the alteration products were dry and powdery and of only limited development. In one specimen sulphur crystals were being deposited on the surface. The dry powder from the exterior consisted of opal, sulphur and unaltered plagioclase and hypersthene crystals. In thin section, it was noted that the plagioclase phenocrysts may be partly replaced by opal and sulphur while fresh feldspars and pyroxene might be traversed by minute veinlets of sulphur. There was a suggestion that sulphur partly replaced the groundmass. In the other specimen, the dry altered lava consisted of opal accompanied by crystals of alunite and tridymite.

LITTLE HOT SPRING VALLEY. In the above cases, transitions to fresh rock are always found, but in road cuts between Supan's Springs and Bumpass Hell (above Little Hot Spring Valley), lavas are exposed that have been completely altered leaving no trace of the original rock and there has been a cessation of thermal activity. Two specimens collected a short distance apart and identical in appearance from a macroscopic examination were partially analyzed (Table II, Nos. 8 and 9) and the differences are quite striking. Assuming that all the alumina is present in the form of kaolin there would be 51 per cent in No. 8 and only 4 per cent in No. 9.

HOT SPRING MUDS. As revealed by microscopic examination, the muds from the hot spring basins consist largely of opal and kaolin accompanied by variable quantities of alunite, tridymite, and residual minerals such as feldspar, pyroxene and zircon with fragments of lava in all stages of decomposition. Some of the muds, e.g., from Devil's Kitchen (Table I, No. 7, Table II, No. 2) may contain considerable quantities of kaolin, while certain of those in Bumpass Hell are colored yellow by much precipitated sulphur. A sample from spring 4, Bumpass Hell, studied by Day and Allen[12] contained 64 per cent sulphur, 17.6 per cent opal, 15 per cent kaolin, 3.3 per cent alunite and a trace of pyrite.

MUD POTS. The mud pots are essentially hot springs with a limited supply of water so that there is no visible outlet, and the basin contains thick pasty mud constantly agitated by escaping gas. Partial analyses of four air-dried muds (Table II, Nos. 3, 4, 6, 7) indicate that kaolin is the chief constituent, an assumption easily verified by the microscope. Finely divided opal is always present, frequently in intimate association with the kaolin. A similar association of these minerals has been reported from the Yellowstone mud pots by Allen.[13] Alunite was observed in 14 out of 18 of the Lassen samples. The mud pots frequently contain many of the residual minerals, such as unaltered plagioclase and pyroxenes, and the apparent concentration of zircon in some sediments is quite striking.

In addition to the minerals, the tests of diatoms were noted in three mud pots, one at Devil's Kitchen and two from Supan's Springs, while a questionable diatom was noted from Bumpass Hell. Diatoms comprising 10 per cent of the sediment have been reported from mud pots near Beowawe, Nevada,[14] but in the Lassen sediments, the diatoms constitute less than one per cent. Dr. G. D. Hanna of the California Academy of Sciences has kindly examined the samples from the mud pots and has reported the following species:

Caloneis bacillum (Grunow). Most common form.
Caloneis latiuscula Kutzing.
Neidium iridis (Ehrenberg).
Pinnularia microstauron (Ehrenberg).
Rhopalodia gibbia (Ehrenberg).

According to Dr. Hanna, these diatoms may very well have lived in the cooler moist portions of the mud pots rather than in the hot mud itself which frequently attains a temperature close to 90°C.

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[12] *Op. cit.*, p. 120.

[13] Allen, E. T., Hot springs of Yellowstone Park: *16th International Geological Congress,* Guidebook **24,** pp. 16 and 23, 1933.

[14] Nolan, T. B., and Anderson, G. H., The geyser area near Beowawe, Eureka County, Nevada: *Am. Jour. Sci.*, 5th ser., vol. **27,** pp. 226–227, 1934.

Boiling Lake. The sediment from Boiling Lake is also composed largely of kaolin (Table I, No. 5). This lake is an oval basin of hot water about 200 yards in largest diameter. Gas bubbles rise occasionally to various points on the surface while the lake is encircled by a chain of hot springs and mud pots, most of which are near the boiling temperature. The temperature of the water in the lake averages about 50°C. The floor of the lake consists of a cream colored mud while the basalt surrounding the basin has been decomposed to reddish and white alteration products.

In addition to the kaolin, which comprises the major portion of every sample examined, small amounts of opal, alunite, pyrite, and, occasionally, iron oxide, may be present. Angular quartz grains were found in some of the samples, and as quartz does not appear in the basalt surrounding the lake, it appears reasonable to assume that it developed as a result of alteration.

Formation of Quartz. At Supan's Springs, some altered material is composed largely of microcrystalline quartz (Table II, No. 5). These specimens are usually harder and more flint-like in appearance than products from the other hot spring areas. In thin section relic porphyritic textures may be recognized but upon inserting the analyzer the rock is resolved into a microcrystalline aggregate of quartz accompanied by minor quantities of alunite and opal. Thin sections of similar character from other areas in the park (Warner Creek, one to two miles below Drakesbad, and at base of Pilot Pinnacle) were loaned to the writer by Dr. Williams. His specimens and those from Supan's Springs are all removed from areas of present active hot springs indicating that the decomposition took place when activity was more widespread and that sufficient time has elapsed for the opal to change to microcrystalline quartz.

However, minor quantities of quartz associated with opal were observed replacing the groundmass of some of the lavas from Devil's Kitchen, and angular quartz fragments were noted in sediments from mud pots and hot springs derived from quartz-free andesites. Several examples of the replacement of tridymite by microgranular quartz were observed. Possibly, therefore, some quartz forms directly. Day and Allen[15] report the presence in two springs of well faceted, double terminated quartz crystals which may have formed during decomposition.

[15] *Op. cit.*, p. 119.

CONCLUSION

In summary it may be stated that opal is the chief product in the altered exteriors of all lava fragments collected where active decomposition is taking place, accompanied by minor amounts of kaolin and alunite. The muds from the hot spring basins may be somewhat similar in composition except that they usually contain more kaolin. The mud pots and the sediments from Boiling Lake all consist largely of this mineral.

Day and Allen suggested that two types of lava decomposition appear to be in progress:

> "the one producing *kaolin* and some *silica without aluminum sulphate*, the other producing *silica with aluminum sulphate*. In the fact that kaolin is decomposed by strong sulphuric acid into silica and aluminum sulphate, the key to the difference is doubtless to be found. If the acid forms in a place where sufficient water is percolating, its concentration is kept down to such a value that the decomposition of feldspars, volcanic glass, and possibly other minerals is incomplete. The intermediate, and comparatively stable compound *kaolin* results, and this, as we have seen generally occurs in the springs, together with very dilute acid. It would not be surprising if the fine sticky mud of the low and wetter portions of the Devil's Kitchen and Bumpass Hell should also prove to contain kaolin, but observations have not been extended to these points.
>
> "On the other hand, if sulphuric acid forms in nearly dry ground it will accumulate by progressive oxidation of the sulphur gases and the concentration may reach comparatively high values—probably in the form of sirupy films. It is under such conditions that this more complete type of rock decomposition occurs, as field observations indicate."[16]

There is considerable evidence in support of their conclusion, namely the high alumina content of the sediments from Boiling Lake where one might expect the greatest dilution of sulphuric acid. Also the mud from Devil's Kitchen near Warner Creek (Table II, No. 4) is from the wetter portions referred to in the above quotation. Moreover, opal is being formed from lavas that are being attacked by steam where the acid may be more concentrated.

But the occurrence in the hot springs of decomposed lava fragments consisting of opal (Table II, No. 1) requires some explanation, if the above conclusion is acceptable. Needless to say, these fragments, if altered in another environment could be transported only a very short distance because of their incoherent character. However, if the rocks above the water level of the springs were attacked by acid developed by condensation of the water vapor and oxidation of the hydrogen sulphide, and this acid were to become concentrated by progressive oxidation, pure opal might form, and lavas so altered might drop a very short distance into the water without loss of form. According to Dr. E. T. Allen[17] this acid formed above the water level of springs at the Geysers, California, may exceed 30 per cent concentration while the strongest sulphuric acid in spring water that he has found (Yellowstone) had a concentration of only 0.4 per cent. This would indicate that rocks attacked by spring water would be subjected to a weak acid while rocks immediately above the water line would be attacked by acid many times the concentration, and would explain why the sediments in the mud pots and springs are richer in clay compared to the rocks above the water level of the springs. The point might be raised that the springs would in time have their outlets lowered owing to the soft character of the altered lavas, and rocks rich in kaolin might then be attacked by more concentrated acid, altering them to alunite and opal, as suggested in the above quotation. However, no specimens were found where there is any suggestion of this although it might be difficult to recognize a relic kaolin-rich stage.

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[16] *Op. cit.*, p. 144.

Another explanation was offered by Day and Allen for the concentration of the kaolin in the mud pots. "Where the springs have an outlet much of the finest material is naturally carried away by flowing water, but where the conditions favor its retention, as they do in the mud pots, the chief constituent of the sediment is kaolin."[18] However, in attempting to separate the kaolin from the opal and alunite, Dr. F. A. Johnson, of the University of California, treated a sample in a centrifuge, and even after prolonged rotation, the kaolin did not separate, and the fact that muds from hot springs with outlets may also contain a large portion of kaolin casts some doubt upon this suggestion. It appears that the high content of this mineral is probably related to conditions of formation rather than to mechanical separation.

Another suggestion for the high concentration of kaolin in the mud pots and hot spring basins might be offered. When one examines the chemical composition of the gases evolved from these hot springs[19] it is seen that CO_2 is the chief constituent. It ranges in amount from 89.80 per cent (spring 24, Devil's Kitchen) to 96.40 per cent (spring 16, Bumpass Hell). On the other hand, the percentage of hydrogen sulphide may range from nothing to 2 per cent, and with most of the gases analyzed, it is less than 1 per cent. There has been no uniformity of opinion regarding the origin of kaolin, some investigators suggesting atmospheric weathering, others pneumatolytic action and others thermal waters. Any of these processes may be operative, but Stremme[20] has ascribed their action in all cases to the chemical activity of carbonic acid. Clarke summarizes the situation by saying, "In short, kaolin, like many other substances, may be formed by any one of several processes, in all of which, water, hot or cold, and carbonic acid take part."[21]

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[17] Personal communication.

[18] Day and Allen, *op. cit.*, p. 119.

Considering that carbon dioxide is the chief gas in these thermal waters, it might be expected that the carbonic acid would attack the rocks in its upward movement and that kaolin would be produced from the feldspars and glass of the lavas forming soluble carbonates and soluble silica. However, soluble carbonates were only reported in three of the spring waters,[22] described as alkaline springs, but if sulphuric acid were formed at the surface, the carbonates would react with the acid to form sulphates with escape of CO_2 into the atmosphere. The soluble sulphates are "those of the *common rock bases, with the exception of alumina*, which, in four-fifths of the samples, varies from 0 to 0.2 mg. per 100 cc., the amount used in analysis. In other words, four-fifths of the waters examined were virtually free from alumina. The more acid waters contain more alumina."[23] However, Dr. Allen[24] explains this by the fact that iron and aluminum are similar in some ways, in that both are held in solution when the sulphuric acid is strong enough, but are precipitated where it is weak. In the case of the alumina, it possibly unites with silica to form kaolin. Dr. Allen has informed the writer that in the Yellowstone Park area, rock is altering to clay in a very few alkaline springs, but the cores of two

[19] Day and Allen, *op. cit.*, pp. 131–133.

[20] Stremme, H., Über Kaolinbildung: *Zeit. für prakt. geol.*, vol. **16**, p. 128, 1908.

[21] Clarke, F. W., The data of geochemistry: *U. S. Geol. Surv.*, Bull. **770**, p. 495, 1924.

[22] Day and Allen, *op. cit.*, p. 111.

[23] Day and Allen, *op. cit.*, p. 110.

[24] Personal communication.

drill holes from the geyser basins studied by Fenner yielded no clay down to depths of 400 feet. The studies of the gases in the alkaline areas showed that most of the free carbonic acid had been combined to form bicarbonates at depths beyond the present range of exploration.

In a recent paper, Allen[25] has suggested that in these alkaline springs of Yellowstone the water supply is large, penetrating to considerable depths so that carbon dioxide is fixed below ground by chemical reaction with the surrounding rocks. But in the sulphate areas, a small water supply limits the depth of penetration of the water, so that atmospheric oxidation of the hydrogen sulphide forms sulphuric acid which attacks the rocks. In alkaline springs, the hydrogen sulphide passes directly into alkali sulphate, instead of sulphuric acid. Presumably in the sulphate springs with a limited downward extension of water, the time element might be a factor in the opportunity of the carbonic acid to react with the rocks, particularly as near the surface, it escapes readily in the atmosphere owing to the heated character of the water.

In summary, it appears that the various types of alteration products are related to the concentration of the sulphuric acid; where the acid is strong, comparatively pure opal will form, as in areas attacked by steam and above the water level of the springs. In the springs and mud pots, as well as Boiling Lake, where the acid concentration is low, kaolin is the important constituent. That the carbonic acid is an effective agent in the formation of the kaolin appears questionable in the light of the results so far obtained from Yellowstone and so kindly reported to the writer by Dr. Allen.

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[25] Allen, E. T., Neglected factors in the development of thermal springs: *Proc. Nat'l. Acad. Sci.*, vol. **20**, pp. 345–349, 1934.

NOTE ON THE LAUE SYMMETRY EXHIBITED BY ORTHOGONAL CRYSTALS

W. H. Barnes and A. V. Wendling.*

In the Laue method of x-ray analysis the most useful photographs are those taken with the beam along the direction of the principal axis or inclined thereto by a few degrees. Consequently, in the case of orthogonal crystals (i.e., orthorhombic, tetragonal, cubic, trigonal, and hexagonal), we are more familiar with the appearance of the diagrams so obtained than we are for those resulting from the beam directed at right angles to this axis and along a lateral (*a* or *b*) axis, except, of course, in the case of cubic crystals. The pictures obtained with the latter settings, however, are sometimes of very great importance. For example, Laue photographs with the beam along the *a* and *b* (orthohexagonal) axes are useful for distinguishing between members of certain pairs of space groups in the rhombohedral division of the hexagonal system.[1]

The object of the present paper is to draw attention to the symmetry exhibited by Laue diagrams of crystals which are characterized by a two-, three-, four-, or six-fold symmetry axis and planes of symmetry containing this axis, but having no plane of simple symmetry normal to it. They may possess two-fold axes perpendicular to the principal axis and not contained in the symmetry planes. The presence or absence of other elements of symmetry does not concern us at present.

There are seven crystal classes which have to be considered, namely C_2^v, C_4^v, D_2^d, T^d, C_3^v, D_3^d, C_6^v.[2]

But in the Laue method, since a center of symmetry is automatically introduced by Friedel's Law due to the inability of the method to distinguish between the parallel planes (hkl) and $(\bar{h}\bar{k}\bar{l})$, other classes show the same Laue symmetry as those enumerated above. They may be grouped together as follows: V, C_2^v, V^h; C_4^v, D_2^d, D_4, D_4^h; C_3^v, D_3, D_3^d; C_6^v, D_3^h, D_6, D_6^h; T^d, O, O^h.

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* Contribution from the Departments of Chemistry and of Physics, McGill University, Montreal.

[1] Barnes, W. H., and Wendling, A. V., *Trans. Roy. Soc.* (*Canada*), vol. **27**, Sect. 3, pp. 133–140, 1933.

[2] For brevity classes will be referred to by symbols. For corresponding names, see Wyckoff, R. W. G., *Analytical Expression of the Results of the Theory of Space Groups*, Carnegie pub. **318**, Table 1, p. 16, Washington, 1930, or Wyckoff, R. W. G., *The Structure of Crystals*, 2nd Ed., Table 1, pp. 22, 23, Chem. Cat. Co., **1931.**

Of these five groups of classes, four exhibit the Laue symmetry of holohedral classes, namely, V^h, D_4^h, D_6^h, O^h. In the Laue method all classes in these four groups appear to possess a plane of symmetry normal to the principal axis and planes of symmetry containing this axis whether or not such planes are actually present in the crystal. In Laue diagrams the fifth group of classes, showing the Laue symmetry of D_3^d, exhibits only planes of symmetry containing the principal axis and no symmetry plane normal to this axis.

Unless this is recognized some confusion may arise in practice when Laue photographs are obtained of crystals belonging to the classes under discussion. For example in Figure 2 the diagram for tourmaline (C_3^v) with the beam along the *b* (orthohexagonal) axis is not symmetrical about the trace of the plane normal to the *c* axis. It appears to be set incorrectly about an axis perpendicular to the *c* axis and parallel to the diagram. Actually the photograph in Figure 2 was obtained as follows. A slip of tourmaline was polished with plane parallel sides of area much larger than the cross-sectional area of the *x*-ray beam. The plane of the polished surfaces coincided with the $(10\bar{1}0)$ plane to within 10 and 15 minutes of arc, respectively, in the prism zone and in the zone normal to the prism. The crystal slip was set optically so that the $(10\bar{1}0)$ plane was normal to the direction of the *x*-ray beam. The beam, therefore, coincided almost exactly with the *b* (orthohexagonal) axis so that the crystal was set correctly.

That the symmetry of the diagram obtained, namely, only about the trace of the symmetry plane $(11\bar{2}0)$, is that which should be expected is clear from the following argument.

In Figure 1(*A*), $\bar{a}Oa$, $\bar{b}Ob$, $\bar{c}Oc$ are three straight lines intersecting at *O* and making angles of 90° with one another.

The figure *MNPQRS* is drawn as a regular bipyramid to avoid unnecessary complications. In the general case each of the points at the corners should consist of four points so that the indices of the faces will be (hkl), $(\bar{h}kl)$, $(h\bar{k}l)$, $(\bar{h}\bar{k}l)$, $(hk\bar{l})$, $(\bar{h}k\bar{l})$, $(h\bar{k}\bar{l})$, $(\bar{h}\bar{k}\bar{l})$, where *h*, *k*, and *l* have different values in each set of indices.

Now since the Laue method makes *O* a centre of symmetry the faces *NRS*, *QRS*, *QPS* and *NPS* appear to be equivalent to the faces *QPM*, *NPM*, *NRM* and *QRM*, respectively. . . 1.

In tourmaline, $\bar{a}Oa$, $\bar{b}Ob$, $\bar{c}Oc$ are the directions of the *a*, *b*, *c*,

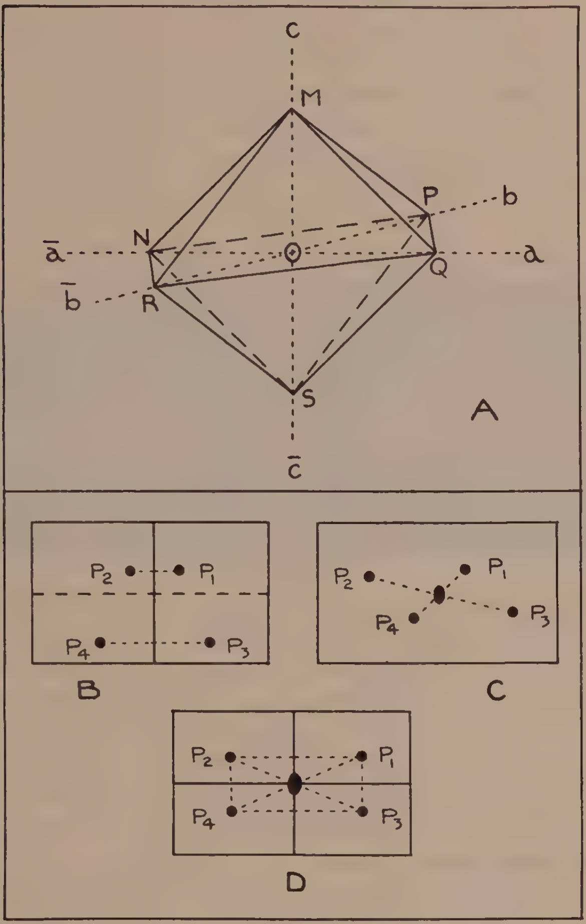

Fig. 1

axes, respectively, in orthohexagonal co-ordinates, and *MRSP* is a plane of symmetry.[3]

Therefore the faces *QPM*, *QRM*, *QPS* and *QRS* are equivalent to the faces *NPM*, *NRM*, *NPS* and *NRS*, respectively. . . 2.

Combining data 1 and 2, the faces *QPM*, *NPM*, *QRS* and *NRS* are equivalent to each other, the faces *QRM*, *NRM*, *NPS* and *QPS* are equivalent to each other, but these two sets of faces are not

[3] Barnes, W. H., and Wendling, A. V., *Trans. Roy. Soc.* (*Canada*) vol. **27**, Sect. 3, pp. 169–175, 1933.

mutually equivalent. Hence *QPNR* does not appear as a plane of symmetry. It will be noted that $\bar{a}Oa$ becomes a two-fold axis of symmetry, because a rotation of the figure through an angle of 90° about $\bar{a}Oa$ as axis brings the mutually equivalent faces *NPM* and *QPM* into coincidence with the equivalent pair of faces *NRS* and *QRS*, respectively, and the mutually equivalent faces *NRM* and *QRM* into coincidence with the faces *NPS* and *QPS*, respectively, to which they are equivalent. Thus the class $C_3{}^v$ possesses the Laue symmetry of $D_3{}^d$.

The general type of symmetry to be expected, therefore, in a Laue diagram obtained with the beam along the direction $\bar{b}Ob$ which lies in the symmetry plane *MRSP* is shown diagrammatically in Figure 1(*B*). The points P_1, P_2, P_3, P_4 arise from the general pairs of planes $(h\bar{k}l)$, $(\bar{h}k\bar{l})$; $(\bar{h}\bar{k}l)$, $(hk\bar{l})$; $(h_1\bar{k}_1\bar{l}_1)$, $(\bar{h}_1k_1l_1)$; $(h_1k_1l_1)$, $(\bar{h}_1\bar{k}_1\bar{l}_1)$, respectively, where h, k and l have not the same values as h_1, k_1 and l_1, respectively. The diagram is symmetrical only about the trace of the plane *MRSP*, shown as a full line in Figure 1(*B*).

Similarly, since $\bar{a}Oa$ appears to be a two-fold axis of symmetry the type of Laue diagram obtained with the beam along this axis may be represented diagrammatically as in Figure 1(*C*) where the points P_1, P_2, P_3, P_4 arise from the general pairs of planes $(\bar{h}\bar{k}l)$, $(hk\bar{l})$; $(\bar{h}_1k_1l_1)$, $(h_1\bar{k}_1\bar{l}_1)$; $(\bar{h}_1\bar{k}_1\bar{l}_1)$, $(h_1k_1l_1)$; $(\bar{h}k\bar{l})$, $(h\bar{k}l)$, respectively, where h, k and l have not the same values as h_1, k_1 and l_1, respectively. The diagram exhibits only the trace of the two-fold axis normal to the diagram shown as an ellipse at the centre, and consequently possesses only a centre of symmetry.

The same types of diagrams are obtained from the classes D_3 and $D_3{}^d$ since both of these also possess the Laue symmetry of $D_3{}^d$.

As mentioned above the other four groups of classes under examination exhibit Laue symmetry elements which make the plane *QPNR* appear as a plane of symmetry in addition to the plane *MRSP*. It will be seen that this makes the two sets of faces 1 and 2 mutually equivalent, so that *QMNS* also is a plane of symmetry, and the Laue diagram with the beam along $\bar{a}Oa$ or along $\bar{b}Ob$ will have the general appearance shown in Figure 1(*D*). It is symmetrical about the traces of the planes *QPNR* and *MRSP* (shown by full lines) which intersect in the trace of the two-fold axis $\bar{a}Oa$ (or $\bar{b}Ob$) which is shown as an ellipse. It is symmetrical, therefore, about two lines at right angles intersecting in a centre of symmetry.

The points P_1, P_2, P_3, P_4 arise from the four pairs of the eight sets of planes constituting the general form $\{hkl\}$, where h, k and l have the same values, respectively, in each set of planes of the form. In the special case of the classes having the Laue symmetry of the class O^h when $\bar{a}Oa$ (or $\bar{b}Ob$) appears as a four-fold axis the distances P_1P_3, P_1P_2, P_2P_4 and P_3P_4 in Figure 1(D) are all equal when the beam is along this axis.

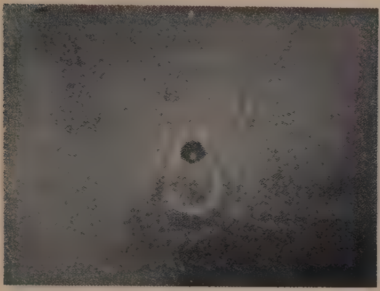

FIG. 2. Tourmaline. Beam ⊥ to $(10\bar{1}0)$

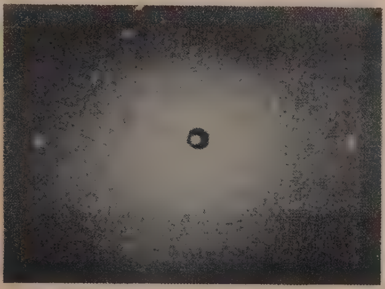

FIG. 3. Calamine (Hemimorphite). Beam ⊥ to (010)

Figure 3 shows the Laue diagram obtained for calamine (hemimorphite), class C_2^v, with the beam along a b axis. The diagram has the symmetry characteristics of Figure 1(D).

The importance of recognizing the symmetry to be expected from Laue diagrams obtained with the beam along a lateral axis in the case of crystals belonging to the classes C_3^v, D_3, and D_3^d is due to the fact that, according to the symmetry exhibited, the space groups C_{3v}^1, C_{3v}^3, D_3^2, D_3^4, D_3^6, D_{3d}^3, D_{3d}^4 may readily be distinguished from C_{3v}^2, C_{3v}^4, D_3^1, D_3^3, D_3^5, D_{3d}^1, D_{3d}^2, respectively. In the former, a axes coincide with two-fold axes of rotation and b (orthohexagonal) axes lie in symmetry planes perpendicular to $\{0001\}$, while, in the latter set, b axes coincide with two-fold axes and a axes lie in symmetry planes perpendicular to $\{0001\}$.

The following experimental procedure, therefore, will allow a rapid and correct choice of space group to be made between the two members of each of these seven pairs.

The possible space groups are reduced to one of these pairs by the usual methods.[4] The crystal is then mounted on a spectrograph equipped with goniometric arcs and a Laue photograph is taken with the x-ray beam along the c axis. The positions of the a and b axes in this picture are readily identified by simple visual inspection. The position of the crystal is altered so as to make one of these axes (say an a axis) coincide with the axis of rotation, leaving the c axis along the direction of the beam. The crystal is rotated through an angle of 90° about the axis of rotation which, in this case, places a b axis in coincidence with the direction of the beam. A Laue photograph is taken with the crystal in this position (i.e., b axis along the beam, a axis along axis of rotation). Finally, the crystal is rotated on the arcs through 30° about the c axis, which is parallel to the plane of the photographic plate. This brings a b axis into the axis of rotation and an a axis along the direction of the beam. A third Laue photograph is taken with this setting (i.e., a axis along the beam, b axis along axis of rotation).

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[4] For example see Astbury, W. T., and Yardley, K., *Trans. Roy. Soc.* (*London*), vol. **224A,** p. 221, 1924.

If there is any doubt as to which axis (a or b) is along the axis of rotation in the last two settings an oscillation or complete rotation photograph for each setting will allow a decision to be made because the primitive translations (a_o and b_o) along the a and b axes are related in such a way that $b_o = a_o\sqrt{3}$.

From the Laue diagrams obtained with the beam along the a and b axes, respectively, visual examination will show immediately if the a axis appears as a two-fold axis (Figure 1(C)) and the b axis as lying in a plane of symmetry (Figure 1(B) turned through 90° about an axis normal to plane of paper since the c axis will be horizontal) or vice versa. If the former then the space group is C_{3v}^1, C_{3v}^3, D_3^2, D_3^4, D_3^6, D_{3d}^3, or D_{3d}^4. If the b axes are two-fold axes and the a axes lie in symmetry planes in the Laue diagrams then the space group is the alternative C_{3v}^2, C_{3v}^4, D_3^1, D_3^3, D_3^5, D_{3d}^1, or D_{3d}^2, respectively.

In conclusion some observations by Hägg[5] on crystals of potassium and rubidium dithionate are of interest. He notes in his paper that both the potassium and rubidium salts show the Laue symmetry D_3^d but only clearly in the photographs of the former. In the case of the latter the diagram along the three-fold axis has the symmetry of D_6^h while that along the two-fold axis is said to agree with D_3^d. The reproduction of his photograph for rubidium dithionate with the beam along a two-fold (a) axis, however, is symmetrical about two lines at right angles intersecting in a centre of symmetry as in Figure 1(*D*). Such a diagram is not compatible with D_3^d.

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[5] Hägg, G., *Zeit. Krist.*, vol. **83**, pp. 265–273, 1932.

Work which we have been carrying out on the dithionates has been hampered very much by the prevalence of twinning. The rubidium salt apparently has a much greater tendency towards twin formation than has the potassium dithionate because, although we have been able to isolate only one crystal of the latter exhibiting the Laue symmetry of D_6^h, we have only obtained one specimen of the former which shows the Laue symmetry of D_3^d. In this case, however, the symmetry of D_3^d was exhibited by the diagrams with the beam along both the two-fold (*a*) and three-fold (*c*) axes. In view of this result it appears that Hägg's crystal of rubidium dithionate may have been twinned.

We are indebted to Dr. R. P. D. Graham, Professor of Mineralogy, for excellent single crystal specimens of calamine (C_2^v), chalcopyrite (D_2^d), tourmaline (C_3^v), calcite (D_3^d), greenockite (C_6^v), and tetrahedrite (T^d) all of which showed the Laue symmetry to be expected of their respective classes. We are also indebted to Dr. F. F. Osborne, Assistant Professor of Geology, for his supervision of the grinding and polishing of the tourmaline slip mentioned above.

THE ROSIWAL METHOD AND THE MODAL DETERMINATION OF ROCKS

Esper S. Larsen and Franklin S. Miller,
Harvard University, Cambridge, Mass.

INTRODUCTION

The present laudable tendency to introduce more quantitative data into petrographic papers makes it desirable to consider critically our quantitative methods, with a view to determining their probable accuracy, the sources of errors in the results, the ways of avoiding errors, and the best methods to secure a required degree of accuracy. Grout (19) discussed the precautions that must be taken in sampling rocks for chemical analyses, and it is the purpose of this paper to point out those that are equally necessary in sampling rocks for micrometric mineral analyses.

Review of the Literature

A number of papers have appeared in the geologic literature since the time of Delesse and Sorby expounding various quantitative methods for the determination of the relative proportions of the mineral constituents in a rock. The first attempts of Delesse (1, 2) involved only tracings of a polished rock surface and so were purely macroscopic. Microscopic methods of measurement were introduced by Sorby (3, p. 21). Two types of quantitative microscopic measurement are in common use at the present time—one areal, the other linear. Johannsen (12) advocates an areal method which makes use of a camera lucida and a planimeter. Lincoln (9) has also used a planimeter to measure areas either on a camera lucida drawing, on a photomicrograph, or on the surface of the rock itself. Thomson (18) has sought to obtain greater accuracy by projecting the image of a thin section upon a blackboard with a lantern and carrying out areal or linear measurements on this enlarged projection.

The linear method of Rosiwal (5) has been simplified by the introduction of recording micrometers for the automatic integration of the measurements—first that of Shand (10) and later those of Wentworth (16) and Hunt (17). Although the fundamental premise of Rosiwal (5, p. 146) that linear (and areal) measurements are directly proportional to the volumes of the minerals measured, regardless of the shape of the individual grains, was challenged by Julien (6) and by Williams (8), it has been satisfactorily defended by Lincoln and Rietz (9) and by Johannsen (12).

With respect to the inherent accuracy of the Rosiwal method, its author pointed out (5, p. 148) that the accuracy is directly proportional to the length of traverse measured and inversely proportional to the grain size of the rock, and that to obtain a measurement accurate to 1 per cent, assuming the greatest possible uniformity of distribution and grain size for the mineral constituents of a rock, the total length of traverse must be at least 100 times the grain size. Lincoln and Rietz (9) hold that this minimum length of traverse is altogether insufficient to reduce the probable error to 1 per cent; and they present formulae derived from the laws of probability and of random sampling for the determination of the probable error in any particular case. When they work through their formulae with a concrete example, they find that the traverse must cross 3,283 mineral grains to insure an error of less than 1 per cent for a granite from Maine. This excessively large figure results from the high degree of probability on which they insist and the geometrical rate at which the necessary number of measurements increases as it approaches the required standard of 1.0 per cent.

Thomson (17) has attacked the problem of the accuracy of these measurements from a more practical standpoint. His experiments on polished sections of synthetic mixtures of pyrite and magnetite in known proportions give average deviations from these proportions of about 1 per cent for linear measurements. The maximum deviation is 3 per cent. The number of grains dealt with is only that contained in an ordinary polished section. On the basis of nearly 100 measurements he concludes that the linear method of Rosiwal is sound and easily capable of an accuracy within 1 or 2 per cent for each constituent and that the areal methods are slightly less accurate.

Holmes (13, p. 317) finds the linear method to be accurate within about 1 per cent for an artificial test field designed especially to check the measurements. The results of a number of Rosiwal determinations tabulated by Johannsen and Stephenson (11) indicate errors of the same order of magnitude, reaching a few per cent as a maximum. Without presenting any experimental data, Grout (19) states that the accuracy of a Rosiwal determination may be within 1 per cent for a rock with grains less than 1 millimeter in diameter, but that for coarse-grained rocks the errors may rise to 20 per cent. Stewart (20) reports differences between two sets of measurements on the same thin section of less than 1 per cent for any constituent, but his differences for two separate thin sections of the same rock amount to as much as 6 per cent.

Two Types of Error in Micrometric Analyses

In any consideration of the accuracy of micrometric analyses, it is important to keep in mind that there are two distinct types of error which may enter into the results: (1) errors caused by failure of the measuring process to give an adequate representation of the thin section to which it is applied and (2) errors due to failure of the thin section to provide a proper sample of the rock from which it is cut. The possible errors arising from these two sources have rarely been distinguished as such in the literature.

Accuracy of Measurements of a Given Thin Section

The errors arising from the measuring process itself will be considered first. In view of the results of the writers cited above and the further experimental results presented below, there seems to be no doubt that the ordinary methods of measurement can be made to yield analyses of a given thin section which will be accurate within roughly 1 per cent for each constituent mineral. Yet attention should be drawn to certain possible errors resulting from the inherent limitations of thin sections as a basis for measurements and from the mechanical limitations of the measuring process.

In the first place, an error may be introduced because the measurements are not made strictly on a single plane, such as the upper surface of the thin section. In the case of opaque minerals, minerals with strong color or high relief, and minerals in very small grains, there is a systematic tendency to over-estimate the amount present by including in the measured intercepts more than actually lies at the upper surface. If the maximum intercept in the thickness of the thin section (0.03 to 0.04 mm.) is recorded, the error would be about 3 per cent of the measured value for intercepts averaging 1 millimeter. For smaller intercepts the error would be greater.

In the second place, it is often tacitly assumed that the investigator is able to determine accurately every grain which is needed for his measurements. Several factors combine to make difficult the elimination of personal errors. The common recording micrometers raise the thin section so far above the level of the microscope stage that the light coming to it from below is seriously cut down, and interference figures are not available to check doubtful grains. Hence, even an experienced worker will frequently find grains of questionable identity. Then since the whole process of measurement is tedious whatever the method employed, eye strain and fatigue combine to invite error. Only the greatest watchfulness and patience in measuring the intercepts and not a little ingenuity in identifying border-line grains will prevent errors from creeping in.

Accuracy of Sampling of a Rock by a Thin Section

Of greater difficulty and importance than the problem of obtaining an accurate measurement of a single thin section is the question of how accurately a thin section samples a rock. Discussions of the Rosiwal method commonly begin with the assumption that the rock is well mixed. Certain it is that many rocks, particularly coarse-grained rocks, are not well mixed on the scale represented by a thin section. The grains of one mineral often tend to be segregated locally into clusters or glomeroporphyritic aggregates. Still more serious in the problem of sampling any considerable body of rock is the frequency with which rocks show pronounced local variations in the relative proportions of their constituent minerals, or even in the assemblage of minerals present.

In the case of moderately coarse-grained rocks, there is the additional difficulty that even though the rock may be well mixed, there may not be enough grains cut by the thin section to provide a satisfactory sample of the rock as a whole. If only a few score or a few hundred grains appear within the thin section, as is frequently the case, the addition or subtraction of one or two grains of a particular mineral at the margin will have an appreciable effect upon the results. The tearing out of grains in the grinding of the thin section is still more serious, because it has a definite tendency to affect relatively resistant minerals, such as hornblende or magnetite, or the coarse phenocrysts in a porphyry. At times it may be possible to estimate from the shape of the holes the character of the grains thus lost and to allow for them accordingly, but this is not ordinarily true.

EXPERIMENTAL DATA

The results of a number of careful Rosiwal determinations made on thin sections of different types of rocks are given below to illustrate the principles just discussed.

ROCKS FROM THE SAN LUIS REY QUADRANGLE, CALIFORNIA: The first two rocks are a granodiorite and a gabbro from the Peninsular Range batholith in the San Luis Rey quadrangle, California. These are ordinary plutonic rocks of moderately coarse grain. The average grain size is slightly more than 1 sq. mm., the few largest grains in each rock reaching an area of 3 to 4 sq. mm. Because of the grain size, an unusually large thin section of each rock was obtained for purposes of measurement. These large sections were subdivided by ruled lines into upper and lower halves, each with an area about equivalent to that of an average thin section, 200 to 300 sq. mm. Two independent sets of measurements and computations were carried out on each half of each section. The results of the successive determinations on the same areas give an indication of the accuracy of the measurements, while a comparison of the two halves of each section shows the amount of variation in composition within a very small area of the rock. As additional evidence bearing on the problem of sampling, there are also presented results of similar measurements upon other thin sections of ordinary size cut from duplicate specimens of the same two rocks. The duplicate specimens come from the same outcrops and from within a few feet of the location of the other specimens.

The measurements were made with a modified Wentworth type recording micrometer (Hunt, 17). The results are given in volume percentages for these rocks, just as they were measured. The stated averages are based directly on the total micrometer readings and are not simply averages of the figures in the preceding columns. The figures for the size of the sections represent the actual area available for measurement exclusive of holes and irregularities. They were obtained by multiplying the average length of the sections by the average length of the individual traverses.

I. *Woodson Mountain granodiorite, San Luis Rey quadrangle, California* (SLR 596).

This rock is a quartz-rich granodiorite which appears in the field to be uniform in composition and grain size. The two thin sections were cut from apparently identical specimens from the same outcrop. The tabulated potash feldspar includes both microcline and microperthite. No orthoclase was observed.

Size of large section: 450 sq. mm.
Size of ordinary section: 300 sq. mm.

Upper Half of Large Section

	1st Measurement	2nd Measurement	Weighted Average
No. traverses	15	10	25
Total length	176 mm.	100 mm.	276 mm.
Quartz	39.3%	38.9%	39.1%
Potash feldspar	23.5	23.6	23.5
Plagioclase	33.5	35.1	34.2
Biotite	2.9	2.4	2.7
Hornblende	0.6	0.0	0.4

Lower Half of Large Section

No. traverses	15	10	25
Total length	217 mm.	138 mm.	355 mm.
Quartz	44.4	45.0	44.6
Potash feldspar	25.8	25.5	25.7
Plagioclase	26.9	26.8	26.9
Biotite	1.1	1.0	1.1
Hornblende	1.7	1.6	1.7

Whole Large Section

				Ordinary Section
No. traverses	30	20	50	14
Total length	393 mm.	238 mm.	631 mm.	254 mm.
Quartz	42.1	42.4	42.2	46.7
Potash feldspar	24.8	24.7	24.8	27.0
Plagioclase	29.9	30.3	30.0	21.6
Biotite	1.9	1.6	1.8	4.0
Hornblende	1.2	1.0	1.1	0.8

II. *San Marcos gabbro, San Luis Rey quadrangle, California* (SLR 218).

This is a hypersthene gabbro which was known to show local variations in the extent to which the pyroxenes were replaced by hornblende. But the hand specimens represented by the two thin sections were taken from the same apparently uniform outcrop and were believed to be as similar as any two specimens of this variable rock. Examination of the thin sections revealed at once marked differences in the proportion of hornblende, as well as the presence of small amounts of quartz and biotite in the smaller section.

Size of large section: 550 sq. mm.
Size of ordinary section: 350 sq. mm.

Upper Half of Large Section

	1st Measurement	2nd Measurement	Weighted Average
No. traverses	18	15	33
Total length	298 mm.	229 mm.	527 mm.
Plagioclase	58.6%	59.0%	58.8%
Pyroxene	29.2	27.2	28.3
Hornblende	3.2	4.5	3.8
(Total pyrobole)	(32.4)	(31.7)	(32.1)
Iron ore	8.9	9.3	9.1

Lower Half of Large Section

No. traverses	18	15	33
Total length	298 mm.	228 mm.	526 mm.
Plagioclase	65.6	65.8	65.7
Pyroxene	19.7	20.5	20.0
Hornblende	7.3	5.8	6.6
(Total pyrobole)	(27.0)	(26.3)	(26.6)
Iron ore	7.4	7.8	7.6

Whole Large Section

				Ordinary Section
No. traverses	36	30	66	15
Total length	596 mm.	457 mm.	1053 mm.	268 mm.
Plagioclase	62.1	62.4	62.2	73.9
Pyroxene	24.5	23.8	24.2	2.3
Hornblende	5.2	5.2	5.2	18.1
(Total pyrobole)	(29.7)	(29.0)	(29.4)	(20.4)
Iron ore	8.1	8.6	8.3	3.3
Quartz	0.0	0.0	0.0	1.5
Biotite	0.0	0.0	0.0	0.8

To test the personal error in measuring the constituents in a single thin section, the large thin section of this gabbro was given to five students for measurement. The students had already made one Rosiwal measurement. One of the measurements differed from the other four by several per cent for both the feldspar and the pyroboles. The range for the constituents and the averages and maximum errors both for all five measurements and for the best four are given below:

	Minimum		Maximum		Average		Maximum error		Measurement by authors
	of 5	of 4	of 5	of 4	of 5	of 4	of 5	of 4	
Plagioclase	59%	61%	63%	63%	61½%	62%	2½%	1%	62.2%
Pyroboles	28½	28½	32½	30½	30	29½	2½	1	29.4
Magnetite	8	8	9	9	8½	8½	½	½	8.3

These data show that with favorable material the constituents in a thin section can easily be measured with a probable error of 1 per cent.

ROCKS FROM IRON HILL, COLORADO: Another group of rocks from the Iron Hill alkaline stock in southwestern Colorado affords an opportunity to compare the results of Rosiwal determinations with those of actual separations of the minerals by heavy liquids. The heavy liquid determinations were made on part of the powder used for chemical analyses of the same rocks. They were checked step by step with the microscope and should be accurate to within about 1 per cent. The results of these separations correspond closely with the chemical analyses. The rocks were especially favorable for heavy liquid separations, but they were rather unfavorable for Rosiwal determinations, since some of them are coarse-grained and some are megascopically variable in mineral composition. To make the results from the separations directly comparable with those from the thin sections, the latter are all stated in weight per cents.

I. *Pyroxenite, Iron Hill, Colorado* (U 1199).

This pyroxenite with a grain size of about 1 mm. appears uniform in the outcrop and in the hand specimen. Four thin sections which were measured with the recording micrometer show surprising variations among themselves and fail to agree closely with the heavy liquid determination or the chemical analysis. The thin sections and the powder used for the analysis and for the heavy liquid separation came from a single block of apparently uniform rock a foot on a side.

Section	1	2	3	4	Weighted Average	Heavy Liquid
Size, sq. mm.	320	200	300	250	1070	
Pyroxene	50%	83%	59%	86%	67%	76%
Apatite	13	3	12	1	7	1
Iron Ore	23	14	29	18	27	17
Perofskite	14					6
Biotite	—	tr	—	—		tr

II. *Shonkinite, Iron Hill, Colorado* (U 2138).

This rock is composed of feldspar crystals up to 40 mm. across, which enclose poikilitically millimeter-sized pyroxene grains. Considering the coarseness of the texture, the agreement of the results given below is very satisfactory. Rosiwal determinations on three thin sections check within 5 per cent of the average, and the latter average checks to within 3 per cent with the heavy liquid analysis.

Section	1	2	3	Weighted Average	Heavy Liquid
Size, sq. mm.	360	420	360	1140	
Altered nepheline Orthoclase	28%	22%	28%	26%	29%
Pyroxene	56	65	59	60	61
Apatite	10	4	8	7	5
Titanite	6	8	4	6	5
Calcite	—	1	1	1	1

III. *Melteigite, Iron Hill, Colorado* (U 1877).

This melteigite is a rock of uniform character with a grain size of about 1 mm. The measurements on two thin sections show variations of 5 per cent from the average. This average agrees with th results of the heavy liquid analysis within 2 per cent.

Section	1	2	Weighted Average	Heavy Liquid
Size, sq. mm.	300	480	780	
Pyroxene	70%	79%	75%	77%
Nepheline	26	18	21	19
Apatite	3	3	3	4
Magnetite	—	tr	tr	tr

IV. *Pyroxene Melteigite, Iron Hill, Colorado* (U 1132).

Since this rock contains grains up to 10 mm. across and is megascopically variable in composition, it is unfavorable for quantitative determinations. The measurements on two thin sections show wide variations, and yet their average checks to within 3 per cent with the results of the heavy liquid separation.

Section	1	2	Weighted Average	Heavy Liquid
Size, sq. mm.	225	320	545	
Nepheline	37%	18%	26%	29%
Apatite	4	4	4	4
Pyroxene	30	38	35	38
Garnet	19	38	28	25
Iron Ore	9	tr	5	2
Phlogopite	4	1	2	1
Calcite	tr	1	tr	1

DISCUSSION OF RESULTS

It is apparent from an examination of the data for the rocks from the San Luis Rey quadrangle that two independent determinations on the same thin section or the same part of a thin section check very closely. The maximum deviation of the percentage of any constituent from the weighted average of all the measurements for that constituent is 1.1 per cent. The average deviation of all the figures from the weighted averages is only 0.2 per cent. Because they are based on only two determinations, the deviations from the weighted averages may be less significant than the actual differences between the two sets of measurements. But the maximum difference between two corresponding figures is 2.0 per cent, and the figures in question are those for the pyroxene in the gabbro. The reason for this discrepancy is that the hornblende is replacing the pyroxene so irregularly and on such a small scale in this thin section, that it is difficult to measure the proper intercepts of the two minerals with the recording micrometer. If the sums of the pyroxene and hornblende are considered throughout, this difference is only 0.7 per cent.

In marked contrast to these close correspondences are the discrepancies between the figures for the two halves of each section and for the large and ordinary sections of each rock. Here the differences reach 8.4 per cent for the plagioclase of the granodiorite, 21.9 per cent for the pyroxene of the gabbro. The change from predominant plagioclase to predominant potash feldspar in the smaller granodiorite section would throw the rock into a different pigeonhole in the classification. Yet the granodiorite appears to be uniform. Close examination of the ordinary thin section shows the different composition of the latter to be due to the presence of a cluster of quartz grains with an unusually high proportion of potash feldspar. It would be necessary to examine a number of additional thin sections before it would be possible to say how common such clusters are or what should be considered the average mineral composition of the rock as a whole. Here is an important problem in sampling.

The gabbro may be considered an extreme example of the variations which are sometimes found in rock specimens collected from a single outcrop, even when they present a similar appearance megascopically. It was not possible to estimate accurately from the hand specimen the relative proportions of pyroxene and amphibole in the rock. A field worker collecting specimens from what looks to be, for this gabbro, a remarkably uniform outcrop would easily be misled into concluding that a single thin section would suffice to sample the outcrop. Yet it is probable that the thin sections now available still fail to cover the range of variation at this place.

For the Iron Hill rocks different thin sections cut from a single block of rock about one foot on a side yielded Rosiwal determinations that varied among themselves by as much as 20 per cent for some of the constituents, and not uncommonly as much as 10 per cent. The averaged results from two to four large thin sections should give satisfactory data for an ordinary rock. Yet in this case the averages are found to differ from the more reliable determinations by heavy liquid separations by as much as 9 per cent. Many of the averages are in error by several per cent.

The tabulated data with regard to the number and total length of the traverses measured on the San Luis Rey sections throw some light upon the question of how many intercepts it is necessary to measure, in order to secure an adequate representation of the mineral composition of a thin section. The number of traverses upon each area of the size of an ordinary thin section varied from 10 to 36, and the total length of these traverses from 100 to 298 mm. The traverses were all made in the same direction across the sections and were spaced at distances of about 1 mm. The degree of correspondence of the results from two independent measurements on the same sections and a theoretical consideration of the problem lead to the conclusion that 10 to 20 traverses across a thin section, spaced about a millimeter apart, will sample that thin section regardless of the grain size. If the maximum grain size is less than 1 mm., even fewer traverses will suffice. Unless the thin section offers some special difficulties to accurate measurement, such as have been indicated above, the results should be correct within 1 per cent for the minerals present in the thin section.

Conclusions

The preceding data and discussion lead to the following conclusions:

(1) The mineral constituents of a thin section can be measured by the Rosiwal method with an error of only about 1 per cent, provided ordinary care and pains are taken. Greater accuracy cannot easily be attained, nor is it necessary or desirable in view of the much larger error which is likely to be introduced through failure of a thin section to sample a rock mass or even a hand specimen.

(2) For an accuracy of about 1 per cent in a Rosiwal determination of a thin section, a satisfactory technique is to make fifteen traverses about a millimeter apart across the section. The traverses should be transverse to any fluidal banding or other linear structure which the rock may show. For rocks with a grain size less than one millimeter fewer traverses will be necessary.

(3) Failure of a thin section to sample a hand specimen or rock outcrop introduces a much larger error than that of the Rosiwal measurement on a thin section. In the experience of the authors, Rosiwal determinations on two or more thin sections from the same hand specimen or small outcrop or even on the two halves of a single large thin section commonly differ by from 2 to 10 per cent for the major constituents, and in some rocks they may differ much more.

(4) For an accuracy of about 1 per cent in a Rosiwal determination of a rock in which the constituents are perfectly mixed, the thin section or surface on which the measurements are made must have an area at least 100 times that of the largest grains that are present to the extent of 1 per cent of the rock. In practice the errors will still often be greater than 1 per cent.

(5) To insure an accuracy of 1 per cent in the measurements for a rock as a whole, determinations should be made on at least two thin sections to test the mixing of the rock. The number of thin sections required to sample a given rock must then be determined by a consideration of the grain size and the uniformity of the rock.

(6) Errors in the measurement of a single thin section increase with decrease in size of grain, because of (1) the exaggeration of the cumulative error from the surface boundary estimation of the opaque minerals, etc., and (2) the increased difficulty in the recognition of the mineral grains. On the other hand, the difficulties of proper sampling increase directly with the grain size, because of (1) the limited number of grains in a thin section, (2) the greater likelihood of improper mixing, and (3) the greater danger of a systematic tearing out of grains in coarse-grained rocks or rocks with coarse phenocrysts. The most favorable rock for measurement is one in which the minerals are uniformly distributed and the grains about 1 mm. across. An ordinary thin section of such a rock will show about 250 grains, and the intercepts will be long enough to measure satisfactorily.

(7) Rosiwal analyses should not be expressed closer than the nearest per cent, except for the minor constituents, without a specific justification of the accuracy for the particular case.

(8) The danger of basing far-reaching conclusions on a few Rosiwal determinations of specimens from widely scattered outcrops is evident. Even if the thin sections used for this purpose are selected with care from a much larger number, as representative of the rock under consideration, there is no assurance that the proportions of the minerals in any one thin section are within less than several per cent of the correct average for the rock mass as a whole.

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THE MINERAGRAPHY AND *X*-RAY ANALYSIS OF STAINIERITE FROM THE SWANSEA MINE, GOODSPRINGS, NEVADA[1]

S. R. B. Cooke[2] and Donald J. Doan.[2]

INTRODUCTION

In conjunction with flotation tests on a cobalt ore from the Swansea mine, Goodsprings, Nev., polished sections were made of the ore and of the concentration products. As the cobalt occurred as hydrated oxide, which is uncommon, its mineragraphic characteristics and *x*-ray diffraction pattern were determined. The crude ore contained 1.23 per cent of cobalt, and the interlocking between the cobalt mineral and the gangue persisted to finer than 400-mesh. Nevertheless, by grinding the ore through 200-mesh, a flotation concentrate was prepared which contained 39.3 per cent of cobalt. The work was done at the Mississippi Valley Experiment Station of the United States Bureau of Mines in cooperation with the Missouri School of Mines and Metallurgy, Rolla, Mo.

Description of Ore

The naturally occurring hydrated cobalt oxides have been poorly described in the literature, and only recently has a satisfactory nomenclature been proposed.

The geology and mineralogy of the Goodsprings quadrangle have been described by Hewett.[3] On the basis of the usual mineralogical blow-pipe tests, the black cobalt-bearing mineral is referred to by him as heterogenite. In the *x*-ray diffraction study, described later in this paper, the writers have concluded that the mineral is stainierite, and henceforth it will be referred to by that name.

Heterogenite is referred to by Dana[4] and Doelter[5] as an amorphous mineral, the composition being given as $CoO \cdot 2Co_2O_3 \cdot 6H_2O$.

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[1] Published by permission of the Director, U. S. Bureau of Mines, as cooperative work between the Mississippi Valley Experiment Station of the Bureau of Mines and the Missouri School of Mines and Metallurgy, Rolla, Mo. (Not subject to copyright.)

[2] Graduate research fellow, Missouri School of Mines and Metallurgy, Rolla, Mo.

[3] Hewett, D. F., Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada: *U. S. Geol. Survey*, Prof. Paper **162,** 1931.

[4] Dana, E. S., *A System of Mineralogy*, 6th ed., New York, **1892,** p. 259.

[5] Doelter, C., *Handbuch der Mineral-Chemie:* Bd. **III,** Heft 2, Dresden, 1926, p. 976.

Schneiderhohn and Ramdohr[6] state that an analysis by Benrath gave approximately the composition $Co_2O_3 \cdot 2H_2O$, probably mixed with a little CoO_2. Schneiderhohn determined the mineral to be optically uniaxial and probably to belong to the hexagonal system. He noted the occurrence of two varieties of the mineral, one crystalline and anisotropic, the other nodular and vitreous, and he refers to both as heterogenite.

Cuvelier,[7] Schoep and Cuvelier,[8] de Jong,[9] and Schoep[10] recently named two varieties of hydrated cobalt oxide on the basis of x-ray diffraction studies. One, giving a definite x-ray diffraction pattern, was named "stainierite"; the other, a vitreous variety giving no x-ray diffraction pattern, retained the name "heterogenite." Cuvelier gives the formula for stainierite as $(Fe, Co, Al)_2O_3 \cdot H_2O$.

Hand samples from the Swansea mine consist essentially of stainierite scattered in a matrix of rhombohedral carbonates. An analysis of a representative sample gave 1.23 per cent of cobalt. The carbonates range from pure white to earthy red and from gray to a light shade of purple. The stainierite occurs as small black specks in the gray and purple carbonate, as larger masses, and as veinlets traversing the reddish carbonate. As a rule the higher the cobalt content the redder and more "rotten" and porous the ore. Occasionally the stainierite occurs as a sooty covering on the carbonates.

The stainierite is black and dull, although a fresh fracture may occasionally appear bright. The rich flotation froth is as black as jet. In no case were macroscopic crystals developed.

Mineralogy and Mineragraphy of the Ore

Gangue Minerals. A sample of the ore was crushed through 14-mesh and the 14- to 20-mesh material was separated with acetylene tetrabromide of 2.95 specific gravity. The product lighter than 2.95 specific gravity consisted of carbonates with very little adhering stainierite. Hand-picking under a low-power microscope effected a separation into four products corresponding to the colored materials mentioned above. Petrographic examination of these products showed that the white mineral was calcite and that the "rotten" reddish material and that having a purplish hue were calcite stained by goethite. The gray carbonate possessed higher refractive indices than calcite, dissolved slowly in cold concentrated hydrochloric acid, and gave a strong microchemical test for magnesium and a weak test for iron. It was identified as dolomite. A small amount of quartz occurred locked with the dolomite. The material heavier than specific gravity 2.95 contained the major portion of the ore minerals.

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[6] Schneiderhohn, H., and Ramdohr, P., *Lehrbuch der Erzmikroskopie*, Berlin, vol. **2**, 1931, pp. 558–59.

[7] Cuvelier, V., Analyse van Enkele Zuivere Stoffen, Technische Produkten en Kobaltmineralien: *Natuurwetenschappelijk Tijdschrift*, Antwerpen, vol. **11**, 1929, pp. 170–79.

[8] Schoep, A., and Cuvelier, V., Sur la Stainierite (un Hydroxide Cobaltique), nouveau mineral: *Bull. Soc. Belge Geol. Pal. Hydrol.*, vol. **39**, 1930 (for 1929), pp. 74–82.

[9] de Jong, W. F., Over Goethiet, Stainieriet, Diaspoor en Heterogeniet: *Natuurwetenschappelijk Tijdschrift*, Antwerpen, vol. **12**, 1930, pp. 69–72.

[10] Schoep, A., Sur la Stainierite et sur un Nouveau Gisement de ce Mineral: *Ann. Service Mines*, Katanga, vol. **1**, 1930, pp. 55–58.

ORE MINERALS. Samples heavier than 2.95 specific gravity and samples of the natural ore were briquetted in bakelite and polished on a modified Vanderwilt polishing machine. Two apparently different opaque cobalt minerals were distinguished in these polished sections. With the exception of a small amount of goethite they were the only opaque minerals observed. The more abundant of the two polished brilliantly, showed strong anisotropism in polarized reflected light, and possessed to a marked degree the property characterized by Schneiderhohn as "reflection pleochroism." In other words, the mineral was markedly anisotropic when no nicols were used. This property is shown in figure 4. In nearly crossed nicols the colors ranged from brown to first order gray. The second mineral was closely associated with the anisotropic variety but polished with a dull mat surface. Some grains showed weak anisotropism; others were quite isotropic.

Microchemical tests of the strongly anisotropic mineral indicated cobalt, a trace of nickel and iron but no manganese. It occurs as:

(1) Irregular veinlets in the carbonates, frequently separated from them by a thin border of the isotropic mineral described above. The surrounding ground mass of carbonates is often replaced by filaments of stainierite. These features are shown in figure 1.

(2) A replacement between individual grains of the carbonates in the ground mass of the ore, as in figure 2. This occurrence is quite common.

(3) A replacement of carbonate along the rhombohedral cleavage, as in figure 3. An example of regular replacement is shown in figure 4, the stainierite occurring as a fretwork between a vein and the matrix.

That the stainierite was originally deposited as colloidal material is fully evident from the sections examined. Figure 5 shows a typical colloform structure.

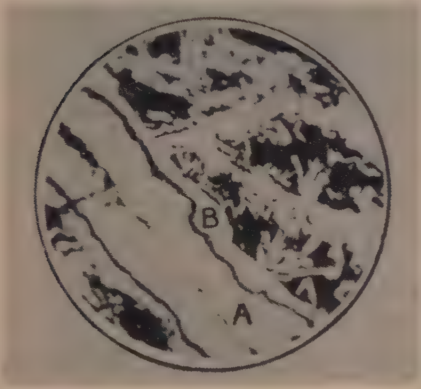

Fig. 1. Veinlet of anisotropic stainierite (A), and filaments of the same in calcite (black). Isotropic stainierite (B). Polished section, vertical illumination, ×200.

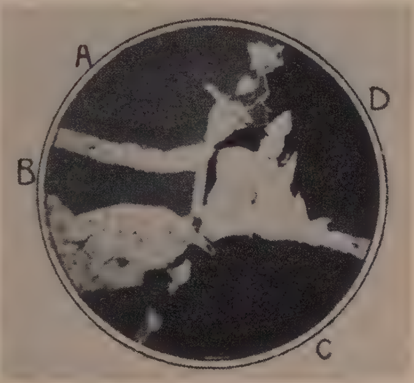

Fig. 2. Anisotropic stainierite (white) replacing carbonates along the grain boundaries. A, B, C, D, rhombohedral carbonate grains. Polished section, crossed nicols, ×200.

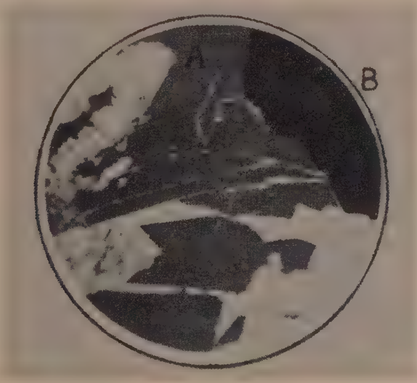

Fig. 3. Stainierite replacing calcite along the rhombohedral cleavages. A, B, individual calcite grains. Polished section, ×200.

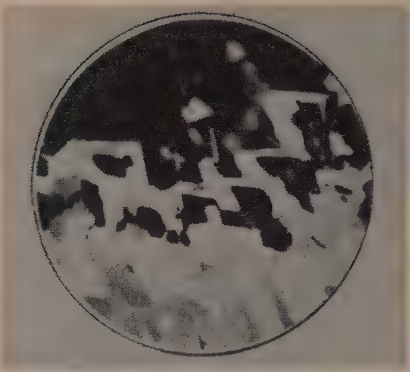

FIG. 4. Regular replacement of calcite by stainierite. Polished section, ×1100.

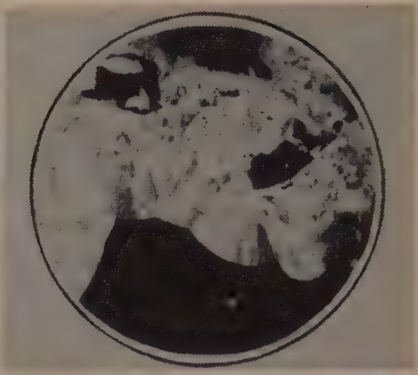

FIG. 5. Colloform stainierite in rhombohedral carbonate (black). Polished section, nicols nearly crossed, ×200.

The second opaque mineral examined was also colloform. Microchemical tests indicated a high cobalt content, a trace of iron, but no manganese or copper. In all probability it is a cryptocrystalline variety of stainierite.

TABLE 1.—MINERAGRAPHIC CHARACTERISTICS OF STAINIERITE

	Etch tests	Color in Reflected Light	Streak	Reflection Pleochroism	Microhardness
Anisotropic variety	Negative to HNO_3, KCN, KOH, $HgCl_2$, $SnCl_2$, H_2O_2. Dissolves slowly in cold HCl with slight tarnish. Dissolves slowly in aqua regia.	Creamy white, yellower than hematite, close to magnetite in color. Brighter than goethite.	Iron gray	Very strong	830 =Talmage E
Isotropic variety	Ditto; no tarnish in HCl.	Dull white.	Dark yellow brown.	—	420 =Talmage D

The various properties of the two microscopically different forms of stainierite are summarized in table 1. Neither variety exhibited any tendency to be attracted by a high-intensity electromagnet. Reducing gases convert the stainierite to metallic cobalt at temperatures about 600° C.

X-ray Diffraction Study

X-ray examinations of a flotation concentrate containing 39.3 per cent of cobalt and of a micro-drill sample of the cryptocrystalline cobalt mineral were made. A modified Siegbahn hot-filament-type *x*-ray tube was used and operated at approximately 25 kilovolts and 10 milliamperes. Hull-Debye-Scherrer photograms were made of the samples by means of a cylindrical camera of 3.929 cm. radius. The radiation used was the K alpha doublet for iron (wave length, 1.934 Angstrom units).

Both fine-grained diffraction lines and spotted lines appeared on the photogram of the flotation concentrate. By direct comparison with standard photograms the spotted lines were shown to be due to rhombohedral carbonates.

The photogram for the micro-drill sample of the cryptocrystalline mineral showed lines which corresponded to the fine-grained pattern of the flotation concentrate. It was thus concluded that both these microscopically different minerals were in reality the same substance, also that the fine-grained pattern was due to the cobalt mineral.

According to de Jong[11] heterogenite is black $Co_2O_3 \cdot H_2O$ and is the amorphous variety of the crystalline material, $Co_2O_3 \cdot H_2O$. This crystalline mineral has been named stainierite. The *x*-ray study thus eliminates heterogenite.

Table 2 gives the *x*-ray diffraction data for the mineral in question.

De Jong's[12] patterns are reproduced diagramatically and do not lend themselves to accurate comparison. However, the above data correspond to those of the mineral stainierite, provided two excess lines which appear in de Jong's pattern are attributed to goethite. The other lines due to goethite correspond approximately to a portion of the stainierite pattern. This assumption seems justified, since de Jong's material contained iron.

[11] *Op. cit.*, p. 72.

[12] *Op. cit.*, p. 71.

The mineral in question is, therefore, identified as stainierite, $Co_2O_3 \cdot H_2O$, the crystalline form of heterogenite.

TABLE 2.—*X*-RAY DIFFRACTION DATA FOR STAINIERITE

Line	Intensity (1–5)	Sin θ	$d_{hkl/n}$
1	2	0.1928	5.02
2	5	.2128	4.55
3	1	.3703	2.61
4	1	.3897	2.48
5	5	.4094	2.36
6	2	.4769	2.03
7	3	.5257	1.84
8	1	.6051	1.60
9	2	.6327	1.53
10	4	.6689	1.45
11	3	.7032	1.38
12	2	.7875	1.22_8
13	1	.7978	1.21_2
14	1	.8171	1.19_5
15	1	.8551	1.13_1

SUMMARY

The occurrence of cobalt in an ore from the Swansea mine, Goodsprings, Nev., is of considerable metallurgical importance, for few cobalt deposits of commercial value are known in the United States and domestic production has been far below the demand.

The cobalt in this ore is present as stainierite, or hydrated cobalt oxide, the crystalline equivalent of heterogenite, with which it has sometimes been confused. The stainierite was identified by *x*-ray diffraction studies.

Microscopically, the stainierite occurs as two varieties, one crystalline and anisotropic and the other cryptocrystalline and isotropic. *X*-ray diffraction studies showed no essential differences between the two.

The mineragraphic properties and *x*-ray diffraction pattern of the stainierite have been determined and are presented in tabular form in this paper.

CROSSED AXIAL PLANE DISPERSION IN TWO ORGANIC COMPOUNDS. A PECULIAR EXTINCTION PHENOMENON

W. M. D. Bryant, *Ammonia Department, E. I. du Pont de Nemours & Co., Inc., Wilmington, Delaware.*

In the course of an optical investigation of an acetaldehyde derivative exhibiting crossed axial plane dispersion and certain other attendant phenomena (1), it was found desirable to examine two other crystalline organic compounds, triphenylbismuthine dichloride and ethyl triphenylpyrrolone, both previously described as having the above type of dispersion. The optic axial angles, 2E, of these materials were measured by means of a petrographic microscope at different temperatures, and for several different wavelengths of light.

The optic axial angles of the bismuthine derivative reported by Greenwood (2) in 1923 agree fairly well with those given below. Greenwood's more recent measurements (3), however, are definitely out of line both with his own earlier work and the results obtained in this laboratory.

Optical axial angles of monoclinic ethyl triphenylpyrrolone were determined by Tutton (4) for three wavelengths of light. Unfortunately, he makes no mention of the temperature of his laboratory, a factor which quite appreciably affects the magnitude of the axial angle. The room temperature was carefully noted all through the present research and experiments conducted to show the maximum difference between the temperatures of the room and of the microscope slide adjacent to the crystals under observation. Because of the temperature uncertainty, Tutton's results are not strictly comparable with those of the writer; the two sets of data, however, agree as to order of magnitude.

Some additional light was thrown on a phenomenon associated with crossed axial plane dispersion and described by Greenwood in his earlier paper (2) on triphenylbismuthine dichloride. Greenwood noted that crystals of the bismuthine derivative, when oriented so that the acute bisectrix coincided with the optic axis of the microscope, and illuminated with white light, act as a light filter and transmit a greenish light practically identical with the wavelength producing uniaxiality, although the crystals themselves are colorless in ordinary light. The effect is observed in the extinction position in parallel polarized light. Two Seignette salts, one uniaxial for green and the other for blue light, were also examined and found to behave in the same manner. Greenwood believed that these peculiar properties were due to rotatory polarization. Since all three of the substances discussed in his article belonged to the bisphenoidal class of the orthorhombic system in which rotation of the plane of polarization often occurs, this explanation at first seemed reasonable. The writer, however, recently observed the same peculiar extinction phenomenon in crystals of a polymorph of acetaldehyde 2:4-dinitrophenylhydrazone which belongs to the monoclinic system and probably to the prismatic class, a circumstance which should, on symmetry considerations, exclude the possibility of rotatory polarization. Further inspection of Greenwood's paper showed that it had not been possible to confirm the presence of optical activity in his compounds by the usual test of obtaining extinction of the residual light by rotation of the analyzing nicol. In view of these facts, it appeared unlikely that rotatory polarization was really responsible for the effect. In order to definitely establish the existence of this "extinction color" in a substance which, on theoretical grounds, should not rotate the plane of polarization, it was decided to examine crystals of a suitable compound of known crystallographic symmetry. Tutton's monoclinic ethyl triphenylpyrrolone (prismatic class) (4) was found to have the desired properties. This substance is uniaxial for a wavelength in the greenish yellow and in the present research was found to transmit the same yellow color in the extinction position when illuminated with white light. It is therefore practically certain in view of the symmetry restrictions that rotatory polarization has nothing to do with the effect.

F. E. Wright[1] of the Geophysical Laboratory of the Carnegie Institution of Washington has offered a simple explanation for the above phenomenon. It is essentially as follows: The colors observed at extinction in crystals of the type just described are similar in origin to the residual light which is observed in many sections of uniaxial and of biaxial crystals and normal to an optic axis. Thus a plate of calcite, cut normal to the optic axis and observed between crossed nicols in parallel light, is not perfectly dark, but is perceptibly illuminated. This lack of complete extinction is due in part to internal reflections, but chiefly to the fact that the transmitted beam of light is slightly convergent or divergent and not strictly parallel. The axial beam which, in convergent polarized light, emerges at the exact center of the interference figure, is quite dark; but beams which include a small angle with the optic axis and which are also transmitted, are not dark, but are more or less colored. In a biaxial section of a crystal of strong birefringence, and normal to an optic axis, this same effect is observed both in convergent and in parallel polarized light. It is enhanced, in parallel light, if the observer shifts his eye across the exit pupil of the eyepiece, thereby emphasizing the oblique portions of the transmitted beam at the margins of the exit pupil.

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[1] Private communication.

In a crystal showing pronounced crossed axial dispersion and uniaxiality for the green or yellow green portion of the spectrum, a section cut normal to the uniaxial optic axis exhibits in convergent polarized light a predominately greenish color near the optic axis. In parallel polarized light the transmitted beam includes, in addition to the waves transmitted along the optic axis, waves whose normals are slightly inclined to the axis with the results that, in this case, the residual extra-axial green light reaches the eye of the observer and colors the section green, or other mid-spectrum hue, at the position of extinction, irrespective of the thickness of the plate.

Besides the five examples cited, F. D. Dodge[2] finds that a modification of lithium acid phthalate is uniaxial for blue and transmits a blue light under the conditions stated above.

EXPERIMENTAL

PREPARATION OF THE CRYSTALLINE MATERIALS: Triphenylbismuthine dichloride was obtained from the Eastman Kodak Company. The original material contained a small amount of a white amorphous solid insoluble in organic solvents but in other respects was practically pure. Crystallizations were made from warm acetone, toluene, benzene-petroleum ether, and chloroform-absolute ethanol. In all cases the first crystallization was followed by a rise in melting point. Additional crystallizations after the first led to a slight lowering of the melting point, probably indicative of a slow spontaneous decomposition of the bismuthine compound.

Crystals resulting from single crystallizations of the Eastman material from acetone and from toluene were employed in a large number of optical measurements. Crystals of the lower melting material resulting from five successive crystallizations of the substance from a mixture of chloroform and absolute ethanol were also examined and found to differ only slightly in optic axial angle from the other preparations. Crystallized melts were obtained by rapid fusion of the recrystallized material on a microscope slide under a cover glass. The freshly cooled melt had optical properties practically identical with those of samples crystallized from solvents. This method of examination, however, was not altogether satisfactory because the thin crystalline films of small phase difference produced rather diffuse interference figures. The fused preparations only remained clear for 10 or 15 minutes, after which time a spontaneous decomposition set in, speedily obscuring the crystals by the formation of amorphous grains.

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[2] Private communication.

Melting points were determined by the capillary tube method employing Anschutz thermometers calibrated by the U. S. Bureau of Standards. The melting points of several samples of triphenylbismuthine dichloride are recorded below:

Material	*Melting Point, °C., Corr.*
Eastman product	138–139°
1st crystallization, acetone	142–145° (shrinkage at 139°)
1st crystallization, toluene	142–145° (shrinkage at 139°)
5th crystallization, chloroform-absolute ethanol	138–139.5°

The fusion was usually preceded by a considerable shrinkage. The high viscosity of the liquid material impaired the precision of the observations by obscuring to some extent the disappearance of the solid phase.

Ethyl triphenylpyrrolone (1-ethyl-3, 3,5-triphenylpyrrolin-2-one) was prepared by the method of Japp and Klingemann (5), using as starting materials benzil, acetophenone and monoethylamine from the Eastman Kodak Company. α-β-dibenzoylstyrene (M. P. 129.5-130.0° C., corr.) was obtained as an intermediate product. The crude ethyl triphenylpyrrolone was slightly yellow in color and melted at 130.2-130.6° C., corr. The yellow color disappeared in the course of three crystallizations from hot absolute ethanol, but the melting point remained unchanged. Inspection confirmed the fact that the crystals obtained were the monoclinic modification. Japp and Klingemann found a melting point of 129° C. for this modification and 123° for the triclinic form. No triclinic crystals were observed in any of the present preparations and the absence of this form is supported by the sharp melting points obtained.

Apparatus: The optical data reported in this article were observed with the aid of a carefully calibrated petrographic microscope. The linear ocular micrometer was calibrated for axial angle work by means of an Abbé apertometer and further checked against a condenser apertometer and a standardized cleavage of mica.

For measuring optic axial angles the source of monochromatic light was the mercury arc, isolating the following lines by means of Wratten filters: 4358, 5461, 5780, 6234, and 6908Å. A partial isolation of the bluegreen line at 4916Å was accomplished by combining Wratten filters No. 48 and No. 75. In determining the wave-lengths for which the crystals became uniaxial, a Schmidt and Haentsch monochromator illuminated by a special Osram lamp was employed. This instrument was calibrated by observing the positions of twelve well characterized spectral lines chiefly from the mercury arc spectrum. White light for microscopy was obtained from a tungsten lamp equipped with a Corning "Daylite" filter.

Temperature measurements were principally those of the room as read from a thermometer placed on the wall near the microscope. The accuracy of these measurements was determined in a series of experiments in which the thermometer readings were compared with those of a No. 30 gauge copper-constantan thermocouple placed on the microscope slide near the crystals under observation. The potentiometer readings, after conversion, were compared with those of a sensitive Bureau of Standards thermometer and found reliable to at least ±0.2° C. The differences between the wall thermometer and the thermocouple readings never exceeded 0.5° C. and were usually less.

Investigation of Optical Properties

Triphenylbismuthine Dichloride: Crystals of this substance in which the acute bisectrix was approximately coincident with the axis of the microscope were selected for measurement of the optic axial angles, their temperature coefficients, and the wave-length of uniaxiality. The individual optic axial angle observations exceeded 360 in number, averaging about 20 observations for each of six wavelengths at three different temperatures. Observations were made in duplicate, the second reading in each case being made after rotating the preparation on the microscope stage through 180°. This procedure was employed to reduce the errors arising from slight departures of the crystals from the correct orientation. Table I contains the average 2E values of the four crystalline preparations examined in this research. These results

TABLE 1.—OPTIC AXIAL ANGLE OF TRIPHENYLBISMUTHINE DICHLORIDE

Wavelength	2E t=20°C.	2E t=25°C.	2E t=30°C.	Axial Plane
		Crystals from Acetone		
4358Å	69.5°	70.3°	70.7°	(001)
4916	38.2	39.8	40.2	(001)
5461	18.2	14.9	12.7	(100)
5780	32.5	31.1	29.9	(100)
6234	43.9	43.0	42.5	(100)
6908	50.5	50.0	49.2	(100)
		Crystals from Toluene		
4358	68.4	69.4	70.4	(001)
4916	39.5	40.3	41.6	(001)
5461	19.2	17.2	14.2	(100)
5780	32.8	32.1	30.4	(100)
6234	44.6	42.9	42.7	(100)
6908	50.9	49.9	49.1	(100)
		Crystals from C_2H_5OH-$CHCl_3$ Mixture		
4358	68.5	69.7		(001)
4916	38.3	40.9		(001)
5461	18.3	15.7		(100)
5780	33.0	31.7		(100)
6234	45.0	43.8		(100)
6908	50.7	50.2		(100)
		Crystals from Melt		
4358		70.3	70.8	(001)
5461		18.5	14.9	(100)
5780		32.4	31.3	(100)
6234		44.8	43.2	(100)
6908		50.8	50.8	(100)
		Average		
4358	69.0±0.5	70.0±0.5	70.5±0.5	(001)
4916	39.0 1.0	40.5 0.5	41.0 1.0	(001)
5461	18.5 0.5	16.5 2.0	14.0 1.0	(100)
5780	33.0 0.5	31.5 1.0	30.5 1.0	(100)
6234	44.5 0.5	44.0 1.0	43.0 0.5	(100)
6908	50.5 0.5	50.5 0.5	49.5 1.0	(100)

are grouped together in a final average at the bottom of the table and the maximum deviation indicated. Since the eyepiece micrometer could be read to the equivalent of ±0.5°, certain real differences in the four preparations become apparent. However, it is believed that these discrepancies represent only slight differences in the purity of the samples.

The approximate temperature coefficient of the optic axial angle could be calculated from the data in Table I. More dependable results were obtained from axial angle measurements on a single crystal over the temperature interval 15-30° C. Values of d(2E)/dt calculated in this way are given below:

Wavelength, Å	4358	4916	5461	5780	6234	6908
d(2E)/dt	+0.1°	+0.25°	−0.55°	−0.25°	−0.25°	−0.15°

It was not feasible to maintain the room temperature at exactly 20, 25 and 30°C. during the optic axial angle experiments. Instead, readings were made when the room was within ±2°C. of the desired temperature, and the small correction applied by means of the above temperature coefficients.

The above measurements of 2E, while not at the same temperatures as Greenwood's results, can be made comparable by extrapolation. This has been done in figure 1. Greenwood's 1923 results (2) in most cases show good agreement with the extrapolated values, the maximum difference amounting to about 5°. This difference may partly be due to the crude character of the temperature coefficients employed. Greenwood includes among his results at 17°C. a uniaxiality value by Barker (temperature unspecified) which agrees poorly with both his own and the present extrapolated data. When this result is excluded from consideration the agreement with the present experiments is much improved. Greenwood's more recent optic axial angle determinations (3), which are supposed to supersede his earlier results, are of a different order of magnitude, as is shown in figure 1. The discrepancy between these later results on one hand and his 1923 data and the present results on the other is negligible at uniaxiality but rapidly becomes greater with increasing optic axial angle, the 1931 results being numerically greater by a factor of about two. Such a divergence is scarcely to be accounted for by differences in the purity of the crystalline material, since contamination would affect the small angles to a greater extent than it would the large. Differences in temperature, wavelength, and composition all tend to produce the most marked changes in angle when 2E is near zero. About the only reasonable explanation of this major discrepancy lies in the possibility that Greenwood's later results are erroneous.

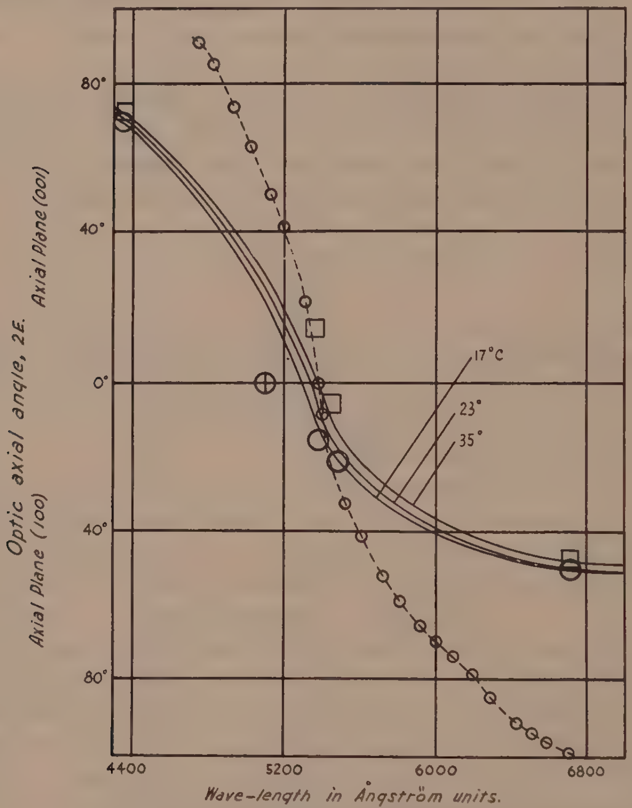

Fig. 1.- Optic Axial Angle of Triphenylbismuthine Dichloride.
○ Greenwood (1923) 17°C.; □ 35° C.; o Greenwood (1931) 23°C.;
⊕ Barker (1923), —— Bryant (1933), 17°, 23°, 35°C. *(Interpolated)*

The wavelengths for which the crystals became uniaxial were determined under the microscope with the aid of a calibrated monochromator. The following results are the averages of observations on about twenty different crystals obtained from the samples employed above:

t°C.	20°	25°	30°
Wavelength of Uniaxiality, Å (present research)	5330±20	5370±20	5385±20
Wavelength of Uniaxiality (Greenwood, 1931)	5368	5392	5410

The reproducibility of this property for any given crystal was about ±5Å. The agreement between different crystals, however, was less satisfactory and did not justify separate treatment of the four samples. Results from Greenwood's later paper are included for purposes of comparison.

The crystals of triphenylbismuthine dichloride used for optic axial angle measurements were correctly oriented for observation of the color phenomenon that is seen in the extinction position under crossed nicols. As stated earlier, this phenomenon is characterized by the ability of the crystal, when illuminated by white light, to selectively transmit a radiation approximately identical in color with that for which the crystal becomes uniaxial. In the position of maximum illumination the crystals transmit a light rich in wavelengths somewhat removed from that of uniaxiality. In the present case the light transmitted at extinction was from the middle green, while at maximum illumination a lavender pink light was transmitted. These colors, unlike those arising from phase difference in ordinary doubly refracting materials, did not vary with the thickness of the preparation. Crystals varying from 0.05 to 2 mm. in thickness were examined in this laboratory and no discernible change in the color of the transmitted light was noted for either of the two positions provided the orientation remained correct. The same effect was also previously observed in similarly oriented crystals of the metastable acetaldehyde 2:4-dinitrophenylhydrazone (1), with the exception that only the extinction color could be observed because of the strong orange color of the crystals themselves.

MONOCLINIC ETHYL TRIPHENYLPYRROLONE: Optical properties of this compound were investigated as in the previous case. The acute bisectrix emerges at an appreciable angle from the normal to the orthopinacoid. Well centered acute bisectrix interference figures could not be obtained from any naturally occurring faces. However, by carefully crushing large crystals of the pyrrolone, occasional fragments of the desired orientation were obtained. In spite of this difficulty the optical properties of various batches of crystals exhibited a constancy that was generally within the error of the determinations.

Optic axial angles at 25 and 30°C. are given in Table 2. These data are the averages of about 120 single observations. A separate investigation over the range 20 to 32.5°C. led to the following approximate temperature coefficients:

TABLE 2.—OPTIC AXIAL ANGLE OF MONOCLINIC ETHYL TRIPHENYLPYRROLONE

Wavelength	2E $t=25°$C.	2E $t=30°$C.	Axial Plane
4358	73.0±1.0°	72.0±2.0°	(010)
4916	45.0 0.5	42.5 0.5	(010)
5461	22.5 0.5	21.0 1.0	(010)
5780	8.0 1.0	10.5 0.5	⊥ to (010)
6234	24.5 0.5	25.5 1.0	⊥ to (010)
6908	31.0 0.5	31.5 0.5	⊥ to (010)

Wavelength, Å	4358	4916	5461	5780	6234	6908
$d(2E)/dt$	−0.2°	−0.3°	−0.4°	+0.55°	+0.25°	+0.2°

Figure 2 shows the agreement between the present optic axial angle data and those of Tutton (4). The temperature of Tutton's experiments is not stated so that an exact comparison is not possible. Inspection of figure 2 suggests that his observations were not all carried out at a single temperature.

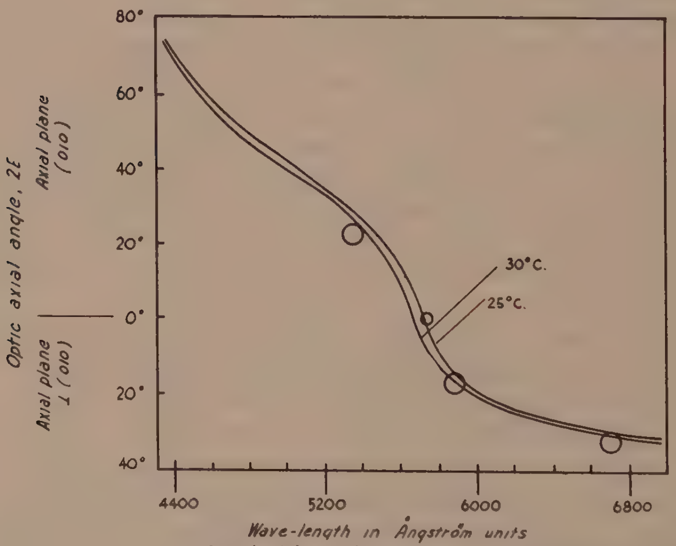

Fig 2 Optic Axial Angle of Monoclinic Ethyl Triphenylpyrrolone
○ Tutton (1890), ○ Tutton (1920), —— Bryant (1933), 25+30°C

The wavelength of uniaxiality was determined at 20, 25 and 30°C. The reproducibility was good throughout and it is believed that the results are correct to ±10 Ångstrom units. They are tabulated below:

t°C.	20°	25°	30°
Wavelength of Uniaxiality, Å	5790	5740	5680

The wavelength of uniaxiality is shifted toward the blue end of the spectrum at the rate of about 12Å for a rise in temperature of 1°C. Tutton determined the wavelength of uniaxiality of this substance as recently as 1920 (6) and obtained a value of 0.000575 mm., temperature unspecified. Assuming Tutton's preparations to be identical with those described above, his measurement would correspond to a temperature of 24°C.

The light transmitted at extinction along the direction of the acute bisectrix under the conditions specified earlier, was of a slightly greenish yellow color corresponding to that of uniaxiality. At maximum illumination a pale lavender color was observed. As in the case of the bismuthine compound, the thickness of the crystal fragment did not affect the color of the light transmitted.

SUMMARY

1. The optic axial angle 2E, its approximate temperature coefficient, and the wavelength of uniaxiality of two organic compounds, triphenylbismuthine dichloride and monoclinic ethyl triphenylpyrrolone, have been determined.

2. A peculiar extinction phenomenon described by Greenwood has been further investigated. Evidence is presented to show that this phenomenon is not dependent upon rotatory polarization as was formerly believed.

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CRYSTAL CLASSIFICATION AND SYMBOLISM

D. Jerome Fisher, *University of Chicago.*

Abstract

In Figure 1 crystals are classified according to increasing symmetry into two phyla (axial and axihedral), three divisions (trimetric, dimetric, monometric), six systems, seven systems and subsystems, seven families (monaxial, polyaxial, anastrephaxial, orthaxihedral, monaxihedral, mesaxihedral, and polyaxihedral), fourteen orders (rows), and thirty-two point groups or classes. This would seem to offer a wide range of choice which might reasonably satisfy all or at least most wants outside of those concerned with crystal structure itself. In addition attention is called to three diagonal rows, which however embrace only 20 of the crystal classes. The Mauguin system of symbolism for both space and point groups is briefly recapitulated, as is the Schoenflies method. The former is recommended.

Introduction

This paper has as its main object the presentation of a classification of crystals in which these solids are so arranged that existing symbolism and nomenclature are more readily comprehended, especially by the beginning student. Apparently nearly every crystallographer (mineralogist, physicist, chemist, metallographer, etc.) who has given much thought to the matter, has had some unique ideas as to the arrangement and designation of crystal classes. The former is of relatively minor significance; the latter is unfortunate, as it tends to cause real confusion.

Present Classification

The chart (Fig. 1) is divided into seven columns on the basis of total symmetry, and into fourteen rows based on the type of symmetry of the (unique) crystal axis. The columns are in two major groupings **(phyla),** depending on whether axes only **(axial)** or both axes and planes **(axihedral)** are present.[1] The rows are in three major groupings **(divisions),** giving the most useful classification of crystals from the optical point of view.

Each column includes three to six crystal classes; this grouping of classes is of morphological value, and so names are given to these **families,** as shown at the top of each column in Fig. 1. The columns are in accord with Schoenflies' symbolism (11, 148–149)[2] as is indicated. The names are similar to those applied by Swartz (12); the significance of each is given in the chart.

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[1] The monoclinic clinohedral class ($Cs = m$) is in the former, since its symmetry can be regarded either as a two-fold inversion axis or as a plane (but it can hardly be considered to be axihedral).

[2] Numbers in parenthesis refer to titles (and page numbers where appropriate) listed at the conclusion of this article.

Each crystal **system** (or **subsystem**) embraces two rows **(orders)**,[3] except there is but one for the orthorhombic and there are three in the isometric. Four rows have but one class each, and six have but two; two rows have three classes each, and two have five. The characteristic symmetry marking each row is shown on the left; it is the same for rows 4 and 5, which are separated because of systematic differences. Omitting the first three rows, each of which has but one class, the number of classes in each pair of rows for 2-, 4-, 3-, and 6-fold axes is 5, 7, 5, 7, 5; the last figure is for the three isometric rows.

This results in 89[4] "boxes" (rectangles), 32 of which represent crystal **classes** or **point groups.** The data given in each of the rectangles are explained at the base of the chart on the left. Excepting the isometric system, five classes may be considered to belong in each family (one for each of a 1-, 2-, 3-, 4-, and 6-fold simple or inversion axis), but duplication and non-crystallographic symmetry reduce this number of 35 to 27, as is explained below.

Schoenflies (11) has three non-isometric families: cyclic (C), dihedral (D), and sphenoidal (S). The first with a single (simple) symmetry axis has three subdivisions which include those classes without planes (C_n), those with a single (horizontal) plane (C_n^h), and those with several (vertical) planes (C_n^v). The dihedral family with symmetry one principal *n*-fold axis and *n* 2-fold axes normal to it also has three subdivisions: those classes without planes (D_n), those with diagonal planes (D_n^d), and those with both vertical and horizontal planes (D_n^h). Moreover D gives way to T (tetrahedral) or O (octahedral) in the isometric, the only system with more than one axis of greater than 2-fold symmetry[5] [and D may be shown as

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[3] To save space, and since combining rows 1 and 2 makes no difference in the sequence of numbering the crystal classes, these are shown as a single row numbered 1–2 in Fig. 1. Class 1 is in row 1 and class 2 is in row 2. Names instead of numbers may be used for the rows as is done for the columns (families); thus row 10 becomes the hexagonal inversion order, row 8 the rhombohedral order, etc.

[4] Boxes III–10 and IV–10 are combined into a single one for reasons pointed out later. Since boxes IV–1 and V–1 are similarly combined, what is referred to as rows 1 and 2 in Fig. 1 contains but 6 boxes.

[5] Since only families with multiple symmetry elements (at least three each of at least two types of symmetry) can be represented in the isometric, it is clear why Cn, Sn, and C_n^h are not so represented. Similarly C_n^v is not represented because while it

V (vierer) or Q (quadratic) in the orthorhombic and in the scalenohedral class of the tetragonal system]. The sphenoidal family (S refers to an alternating axis) has two analogous subdivisions (see footnote 14). The writer's families thus agree with Schoenflies' sub-divisions, but his two major groupings (axial and axihedral) contrast with those of Schoenflies.

Monaxial family (column I of Fig. 1) includes those classes with but a single (simple) rotation axis of symmetry and with no other symmetry. Of necessity such axes are polar, and the crystals may be regarded as hemimorphic.[6] Rotatory polarization as well as pyro-and piezo-electric phenomena are possible in the crystals of this family. Since the only simple axes occurring in crystals are 2-, 3-, 4-, and 6-fold, these four classes and the one with no symmetry at all (which may be regarded as having a simple 1-fold rotation axis) complete this simplest family. The Hermann-Mauguin symbol[7] (7) for each of these classes is the same as the expression of the total symmetry by this system of notation, the principles of which are explained in the lower right portion of Fig. 1.[8]

Polyaxial family including those classes with several symmetry axes, but lacking planes or center, contains all enantiomorphous[9]

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may be considered as polysymmetric, its symmetry is "one-dimensional" (all elements parallel one direction), not "three-dimensional" as required by the isometric. Thus only three families can have isometric representatives, and since there are only three types of "principal axis" (Fig. 1) present in this system, and one of these is an inversion axis, it is clear that at most two isometric classes can occur in any one family, and but one can occur in that polysymmetric family (mesaxihedral) characterized by the presence of an inversion axis.

[6] Hilton (5, 92) includes only those crystals in class no. 4 ($C_2=2$) of Fig. 1 of the monaxial family as hemimorphic, although the symmetry axis in each of the monaxial classes is polar. If hemimorphic forms are limited to those which may be regarded as but half (one end) of the corresponding holohedral forms, then monaxial classes of the dimetric division are not hemimorphic; Dana's *Textbook of Mineralogy* (1932 ed. by W. E. Ford, pp. 103, 118, 131) states that they are hemimorphic.

[7] This type of symbol, first proposed by C. Hermann, was greatly simplified and owes its present form to the efforts of Ch. Mauguin.

[8] W. Soller (*Am. Mineral.*, vol. **19**, p. 412, 1934) unfortunately suggests that the Mauguin symbol for the even-numbered inversion axes be used for alternating axes instead; the rule of priority, if no other, prohibits the acceptance of this suggestion.

[9] Hilton (5, 92) does not list class no. 28 ($T=23$) of Fig. 1 as containing enantiomorphous forms. Tutton (14, 131) lists the eleven classes of the monaxial and polyaxial families as enantiomorphous, as does Jaeger (6, 79), who links this property with optical rotatory power, at least in most cases (pp. 256, 261–262, 268). If screw axes are essential for optical rotatory power, representatives of class 1 and of certain space groups (see Table 3) of all other monaxial and polyaxial classes

forms. Rotatory polarization is also possible in the crystals of this family, as it is among those of the monaxial family, though difficult to observe in crystals of those classes of these families belonging in the trimetric division. Representatives of classes Nos. 17 and 28 may show pyro-and piezo-electric effects. The non-isometric crystals of the polyaxial family are characterized by one n-fold axis with n 2-fold axes normal to it. If $n=1$, the symmetry is that of the monoclinic sphenoidal class ($C_2=2$); thus only four non-isometric classes appear in this family.

The **Hermann-Mauguin symbol** for each of the polyaxial classes (except $D_2=222$) is a simplification of the expression for the total symmetry, as is indicated in Fig. 1. Mauguin (7, 545) does not use superscripts as shown in parentheses in certain rectangles of Fig. 1 to indicate the total number or amount of any given kind of symmetry element present. In the dimetric division his symmetry elements are listed in this order: vertical axis, horizontal axis and/or (horizontal or vertical) planes, if any; where there are 2-folds normal to the planes (and therefore centers of symmetry) this is not specifically indicated by Mauguin's slightly abbreviated symbolism which drops the 2; this is also true in the orthorhombic and isometric systems. In the isometric Mauguin lists the symmetry elements in this order: axes parallel cube edge, cube diagonal, and cube-face diagonal; 4-folds normal to planes (class No. $32=O_h=m\,3\,m$) or 2-folds in the third place (class no. $31=O=43$) are not indicated in the abbreviated point-group symbolism. Each isometric point-group has the numeral **3** as the *second* unit of the point-group symbol, whereas **3** is the *first* unit in the symbol of each of the five rhombohedral classes, none of which has a horizontal plane of symmetry.

Anastrephaxial[10] **family** (sphenoidal of Schoenflies) includes those classes with but a single inversion axis of symmetry (rotary inversion); these classes can also be derived in terms of single alternating axes of symmetry (rotary reflections). In fact an inversion 4-fold gives the same results as an alternating 4-fold; otherwise the correspondence is less obvious, as shown by Table 1.[11] The

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must lack this property. Screw axes also occur in various space groups of $D_{2d}=\bar{4}2m$ and of all orthaxihedral classes except $C_{3h}=\bar{6}$. See F. Bernauer: Gedrillte Kristalle, 1929.

[10] Term derived from the Greek *anastrepho* (turn upside down, invert) and *axon* (axis), with the kind assistance of Professor G. E. Smith.

[11] Classes developed from only the even-numbered inversion axes form the

TABLE 1. CORRESPONDENCE BETWEEN ALTERNATING AXES AND INVERSION AXES

Alternating Axes (Sn) (rotary reflections)	Inversion Axes (C_n^i) or (nc) or ($\bar{n}$) (rotary inversions)
S2	$Ci = C_1^i = \bar{1} = i$ (inversion or center)
S=S1	$2c = \bar{2} = m$ (plane)
S6	$C_3^i = \bar{3}$
$C'_4 = S4$	$4c = \bar{4}$
S3	$6c = \bar{6} = 3/m$(3-fold with normal plane)

writer prefers the inversion axes because $\bar{3}$ (3-fold inversion axis) is found in the rhombohedral subsystem, $\bar{6}$ in the hexagonal subsystem, whereas the reverse is true if alternating axes are used, the tendency then being to hide the true symmetry relationships as is shown by the fact that some writers include hexagonal classes in the rhombohedral and vice versa. Moreover, if alternating axes are used, putting what corresponds to the anastrephaxial family in the axial phylum might seem inconsistent.[12] The Herman-Mauguin symbol for each of the anastrephaxial classes is the same as the expression of the total symmetry by this system of notation, as is true for the monaxial family. Pyro- and piezo-electric phenomena are possible in the crystals of class no. 3 (Cs=m) of this family. As those other classes in this family in which n is odd have a center of symmetry, their representatives cannot be expected to exhibit such phenomena (6, 101).

Orthaxihedral family, each class of which has but one axis normal to one plane, has but four classes, as where $n=1$ the symmetry is the same as that of the monoclinic clinohedral class (Cs=m), placed by preference in the anastrephaxial family. In the classes of this family in the dimetric division, as in those of other families that have both axes and planes of symmetry, are the di-forms, except disphenoids. Orthaxihedral classes except

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groups nc (17, 15) and lack a center of symmetry. Classes derived from only the odd-numbered inversion axes have a center of symmetry, and Rogers (10, 172) prefers to refer to these only as alternating axes ("rotoflections"). Only the latter (anastrephaxial) classes are given the symbol C_n^i, which may also be used for orthaxihedral classes nos. 5, 13, and 25 of Fig. 1 (17, 15). All these symbols have been conveniently summarized by Davey (3, 218–221).

[12] Of course the "alternating planes" are present, whether the symmetry is regarded as alternating axes or inversion axes. Classification is primarily for purposes of convenience in bringing out certain relationships which one wishes to emphasize. Therefore it is considered permissible to put this family where it is in Fig. 1. Swartz (12) chose to stress alternating axes; therefore used the term *amebaxial*.

class no. 5 ($C_2^h = 2/m$), the holohedral of the monoclinic system, are paramorphic, as is also class no. 29 ($Th = m3$) of the isometric (5, 92). Orthaxihedral classes in which n is an even number have a center of symmetry.[13]

Monaxihedral family which contains classes with several planes of symmetry meeting in one axis of symmetry, has but four classes, as where $n=1$ there could be but one plane, which leads to the monoclinic clinohedral class ($Cs = m$) of the anastrephaxial family. The axis is polar and the representatives, which may show pyro- and piezo-electric effects, are hemimorphic (cf. monaxial family), as are those of class no. 30 ($Td = \bar{4}3m$) of the mesaxihedral family, according to Hilton (5, 92). Ordinary polar axes are not confined to the monaxial and monaxihedral families, but are also found in classes nos. 17 (quartz), 22 (benitoite), 28 (cobaltite), and 30 (sphalerite) of Fig. 1. Representatives of all these (as well as those of class no. $3 = Cs = m$) may exhibit pyro- and piezo-electric phenomena. The Mauguin symbol (mm) for class no. 7 (C_2^v) of the monaxihedral family does not directly show the 2-fold axis present, since if a crystal has but two perpendicular planes of symmetry, their line of intersection must be a 2-fold axis.

Mesaxihedral family, including those classes with both planes and symmetry axes, but with no plane containing more than one symmetry axis, and all planes lying midway between (Greek *mesos*) symmetry axes, embraces but two non-isometric classes, as is indicated in Fig. 1. Where $n=1$, this family produces class no. 5 ($C_2^h = 2/m$), already placed with the orthaxihedral family. Where $n=2$ and 3, this results in classes nos. 10 and 20 of the mesaxihedral family, whose principal axes have symmetries of $\bar{4}$ and $\bar{3}$ respectively, higher than those of the starting symmetry because of the demands of the planes and the other axes. Similarly where $n=4$ and 6, this leads to principal axes of alternating 8- and 12-fold symmetry respectively, axes non-existent in crystals.

The mesaxihedral family thus bears a close relation to the anastrephaxial family; in each class in either family the principal axis is an inversion axis, or may also be regarded as an alternating axis.[14]

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[13] It should be pointed out that class no. 21 ($C_3^h = \bar{6}$) may be placed equally well with either the anastrephaxial or orthaxihedral families as is indicated in Fig. 1. Schoenflies preferred it in the latter as shown by his choice of symbol (C_3^h instead of S3). Mauguin's choice of symbol ($\bar{6}$ in place of $3/m$) indicates the reverse, probably because he wished to emphasize its hexagonal symmetry. It is the only non-Triclinic class represented by but a single space group.

[14] Thus Schoenflies gave S_4^u as alternative for D_2^d and S_6^u as alternative for D_3^d,

In no other classes are inversion axes present as crystal axes, except in class no. 22 (benitoite)[15] of the polyaxihedral family [and also excepting class no. 21 ($C_3^h=\bar{6}$), included in both orthaxihedral and anastrephaxial families of Fig. 1]. The classes of the anastrephaxial and mesaxihedral families having *n* an odd number contain a center of symmetry. Representatives of those lacking a center of symmetry (excepting the tetragonal classes) may exhibit pyro- and piezo-electric phenomena.

Polyaxihedral family with several planes of symmetry each of which includes at least two axes of symmetry (four in class no. $32=Oh=m3m$) embraces but four non-isometric classes, as where $n=1$, this leads to class no. 7 ($C_2^v=m\ m$) in the monaxihedral family. The family includes four holohedral classes. As is true of the classes of the orthaxihedral family, all polyaxihedral classes with *n* an even number have a center of symmetry, as do the two isometric classes of this group. The latter are therefore the only isometric classes having inversion 3-folds. Representatives of class no. 22 ($D_3^h=\bar{6}m$) are the only ones which may exhibit pyro- and piezo-electric phenomena.[15a]

General Discussion

It will be noted that twenty of the classes lie on three **diagonal rows** trending northwest-southeast (map parlance) in Fig. 1. These diagonal rows consist of classes numbered 1,[16] blank, 3, 5, 7, 10,

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S_n signifying a rotary reflection and the u (Umklappung) referring to rotation about the 2-fold axes.

[15] Class no. 22 ($D_3^h=\bar{6}m$) is here put in the polyaxihedral family because each of its planes *contains* two symmetry axes; i.e., it is *not* mesaxihedral (see footnote 18). Mauguin (7, 545) chose $\bar{6}\ 2\ m$ as its symbol, which is analogous to the symbols of the mesaxihedral classes. Bernal et al (1, 529) have since abbreviated this to $\bar{6}$ m. Had the symbol 3/m 2 m (or 3/m m) been chosen, this would have tended to hide the hexagonal nature of the class, but the present symbol serves to mask its true family relations. Bragg (2, 86) puts $\bar{6}$ m with $\bar{4}$ 2 m (no. 10 of Fig. 1) forming the groups n d (17, 15) and with $\bar{4}$ 3 m (no. 30 of Fig. 1), and places $\bar{3}$ m (no. 20 of Fig. 1) in his last column, which thus consists of five holohedral classes (all except monoclinic and triclinic, assuming a holohedral rhombohedral class) forming the groups D_n^i (17, 15) plus $Oi=Oh$.

[15a] Willi Kleber has recently (*Centr. Min., Geol. u. Pal.* A(9), pp. 241–250, 1934) derived the 32 classes by using the stereographic projection. He puts them in six families: cyclic (5 classes), dihedral (4-none isometric), gyroidal (3 plus $C_3^h=\bar{6}$), spiegel (14 plus $C_3^h=\bar{6}$), tetrahedral (3), and octahedral (2). Cyclic is monaxial; dihedral is polyaxial lacking isometric representatives; gyroidal is anastrephaxial less $Cs=m$; tetrahedral and octahedral embrace the isometric classes; and spiegel includes all the rest.

15–4, 6, 9, 13, 18, 20, 22–11, 17, 19, 21, 25, blank, 30, 32. Each diagonal row is separated from its neighbor by two boxes (going vertically), except the right hand part of the lowest diagonal row is shifted one box lower because of the intermediate nature of class no. 21 ($C_3^h = \bar{6}$). These three diagonal rows sweep across the whole chart from class no. 1 to class no. 32. The major significance of these diagonal rows seems to be that they indicate a proper sequence of class arrangment; that is, as one proceeds downward across the rows (orders), thus in general increasing the symmetry of the "Principal Axis" (Fig. 1), one also goes with equal regularity to the right from one family (column) to the next, thus more or less automatically adding on other (consequential) elements of symmetry.

While rows 3, 4, and 5 can be collapsed into one, as can rows 6 and 7, 8 and 9, and 13 with 12 or 14, the diagonal rows are then destroyed. Suppose the tetragonal classes (rows 6 and 7) are put intermediate between the rhombohedral and hexagonal classes, as has been done by some;[17] then the diagonal row symmetry is almost completely removed. The polyaxial family can be bodily interchanged with the anastrephaxial family without even altering the class numbers; in fact the writer's first charts did this. But then the diagonal symmetry is broken.[18] Although several simple axes (polyaxial family) may seem to some to be more complex

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[16] What is shown as the top row in Fig. 1 in reality consists of two rows, as is indicated by the numbering on the right.

[17] The basis for this is presumably the fact that the 3-fold type of axis is regarded as having a lower grade of symmetry than does the 4-fold. This is incorrect, as can be seen by comparing an alternating 4-fold with the simple and inversion 3-folds. By analogy then the inversion 6-fold (row 10) should be separated from the 6-fold (row 11) by the 4-fold (row 7), thus splitting the hexagonal subsystem itself. If rows are arranged in the order of 3, $\bar{4}$, $\bar{3}$, $\bar{6}$, 4, 6, there is one partial diagonal row, which however does not join with either trimetric or monometric classes. If put in the order 3, $\bar{4}$, $\bar{6}$, $\bar{3}$, 4, 6 there are three diagonal rows (two of them partial), two of which are "hanging," but the third and major one (which however is partial, having two blanks) joins class no. 29 ($Th = m\ 3$) of the isometric. Neither of these arrangements compares favorably with that of Fig. 1 from the point of view of diagonal rows. Moreover the very close relationship between hexagonal and rhombohedral subsystems is sufficient to preclude the desirability of separating them by the tetragonal system.

[18] A further note regarding the position in Fig. 1 of class 22 ($= D_3^h = \bar{6}m$) is here justified, as it will be noted that were this class put as straddling the mesaxihedral and polyaxihedral families, it would add one more class (no. 27) to the intermediate diagonal row; moreover both (all) the classes of the hexagonal inversion order would then be of this duplex nature. If the definition of the mesaxihedral family be changed to read "with all planes lying midway between *crystal* axes (which are *not*

than a single inversion axis (anastrephaxial family), this is not true, since the latter involves two kinds of symmetry, the former but one. In reality the anastrephaxial family is intermediate between families I and II and the families of the axihedral phylum; this is indicated by the intermediate position of class no. 21 ($C_3^h=\bar{6}$); by the fact that most morphologists think of class no. 3 (Cs = m) as having symmetry of but one plane, no axis;[19] and by consideration of the two kinds of symmetry present in the symmetry unit of each class of the anastrephaxial family. It may also be added that the eleven classes of the monaxial and polyaxial families which are in juxtaposition in Fig. 1 are the ones containing only symmetry elements of the first sort (involving nothing but simple rotations), and so correspond to those derived first by Schoenflies (11, 74).

Space Lattices and Space Groups

The advantages of the Hermann-Mauguin over the Schoenflies symbolism are not apparent from Fig. 1 or from any study limited to the point-groups (crystal classes). For that reason there is here added Tables 2 and 3 which show the extension of this symbolism to the 230 space groups. Table 2 summarizes the data regarding the fourteen Bravais space lattices and their five variants. In space group terminology no subscripts indicating the system as shown in the table are necessary, since the system of the lattice in question is apparent from the other symmetry indicated by the Mauguin symbolism.[20] There are taken to be but six primitive lattices, as is shown in Table 2, since the hexagonal lattice *Ch*

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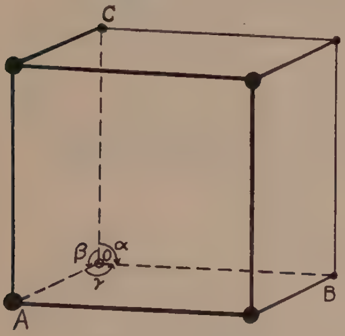
symmetry axes in class 22)" and if the qualification of "no plane containing more than one symmetry axis" be omitted, then class 22 would properly be regarded as belonging to both families. The position shown in Fig. 1 is however preferred, since the whole table is based on symmetry and not on crystal axes (where the two do not coincide), and it hardly seems wise to make an exception for a single class. Moreover some have made the *a*-axes coincide with the 2-folds in this class (e.g., see 18, 37; 12, **31**; and 16, II), although this is unfortunate, since it makes the first order forms hexagonal and the second order forms trigonal, contrary to the order in all other hexagonal classes. For examples of proper orientation see 10, 190; 16, III, VII; and Ford: Dana's *Textbook of Mineralogy*, 1932, p. 119. In addition with class 22 left as it is in Fig. 1 there is the normal number of five non-isometric classes in the polyaxihedral family (allowing for duplication), as is also true for the mesaxihedral family (remembering that two classes are missing from this family because of the non-occurrence in crystals of 8- and 12-fold alternating axes).

[19] Thus it has been called the anaxial class (*Am. Mineral.*, vol. **12**, p. 219, 1927).

[20] *Pa* (anorthic) is preferred for brevity to *Ptr* (triclinic). While *R* is the standard

(which is also primitive in the ordinary sense of the word) may be regarded as a special case of the (001)-centered orthorhombic (three pinacoids) lattice (*Co*) where the edges a:b=1:$\sqrt{3}$. The rotation of the *a*-axis of this lattice 30° produces the larger variant designated *H*.[21]



Primitive Lattice

TABLE 2. THE FOURTEEN BRAVAIS SPACE LATTICES

Six primitive lattices (*P*)
[Call OA=a, OB=b, OC=c]

	edges	*angles*	
Pa[*Ptr*]	. . . $a\neq b\neq c$ . . .	$\alpha\neq\beta\neq\gamma\neq 90°$	three pinacoids
Pm	. . . “	. . . $\alpha=\gamma=90°\neq\beta$	
Po	. . . “	. . . $\alpha=\beta=\gamma=90°$	
Pt	. . . $a=b\neq c$ . . .	“ . . .	2° tetragonal prism and pinacoid
Pi	. . . $a=b=c$ . . .	“ . . .	hexahedron
R[*Pr*]	. . . “	. . . $\alpha=\beta=\gamma\neq 90°$ . . .	rhombohedron

Three body-centered lattices (*I*)

Io corresponding to *Po*; *It* corresponding to *Pt*; and *Ii* corresponding to *Pi*.

Three lattices with a single centered (001) face (*C*) **[plus four variants marked*]**

Cm (cf. *Pm*); *Co* (cf. *Po*. . .variants are **Ao* and **Bo* which are the same except for orientation); **Ct* (cf. *Pt* of which it is a variant); and *Ch* (special case of *Co* where $a:b=1:\sqrt{3}$. . .variant **H* is similar except rotated 30°, so that $a:b=\sqrt{3}:1$; lattice *Ch* is same as that consisting of a 60° orthorhombic prism with basal pinacoid, three of which units form a hexagonal prism with centered basal pinacoid).

Two lattices with all faces centered (*F*); **[plus one variant marked*]**

Fo (cf. *Po*); **Ft* (cf. *Pt*. . .variant of *It*); and *Fi* (cf. *Pi*).

. . . .

Notes: *Cm* and *Co* may be regarded as rhombic prisms with basal pinacoid. *Fo* is same as body-centered orthorhombic prism with basal pinacoid; it is also the same as an orthorhombic dipyramid. *Io* is same as orthorhombic brachy- and macrodomes. *Ct* is same as four units of *Pt*. *It* is same as a second order tegragonal dipyramid; rotating it 45° to the first order form (and translating it parallel *c* one-half the unit distance) leads to the variant *Ft*. *Fi* corresponds to the octahedron, or the rhombohedron with 60–120° face angles, four of which rhombohedra constitute a dodecahedron. *Ii* corresponds to the rhombohedron with face angle of 109° 28′.

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symbol for the rhombohedral lattice, *Pr* might be preferred by some morphologists since it better indicates the analogy with the other primitive lattices.

[21] Schiebold (9, 32) uses *Ch* for this, and *Ph* for the lattice designated *Ch* by Mauguin. From the point of view of space group notation it is better to omit *P* from the designation of either hexagonal or rhombohedral lattices.

TRIMETRIC SPACE GROUPS

Space Group Number	Class No. Schoenflies Symbol	Schoenflies Number	Mauguin symbol	
			Normal orientation	Other orientations
1	1–C1	1	P1	A1, B1, C1, F1, I1, . . .
2	2–Ci	1	$P\bar{1}$	$A\bar{1}$, $B\bar{1}$, $C\bar{1}$, $F\bar{1}$, $I\bar{1}$, . . .
3	3–Cs	1	Pm	Bm
4		2	Pc	Pa, Pn, Ba, Bd
5		3	Cm	Am, Im, Fm
6		4	Cc	Aa, Ia, Fd
7	4–C2	1	P2	B2
8		2	$P2_1$	$B2_1$
9		3	C2	A2, I2, F2
10	5–C2h	1	P2/m	B2/m
11		2	$P2_1/m$	$B2_1/m$
12		3	C2/m	A2/m, I2/m, F2/m
13		4	P2/c	P2/a, P2/n, B2/a, B2/d
14		5	$P2_1/c$	$P2_1/a$, $P2_1/n$, $B2_1/a$, $B2_1/d$
15		6	C2/c	A2/a, I2/a, F2/d
16	6–D2	1	P222	—
17		2	$P222_1$	$P2_122$, $P22_12$
18		3	$P2_12_12$	$P22_12_1$, $P2_122_1$
19		4	$P2_12_12_1$	—
20		5	$C222_1$	$A2_122$, $B22_12$
21		6	C222	A222, B222
22		7	F222	—
23		8	I222	—
24		9	$I2_12_12_1$	—
25	7–C2v	1	Pmm	—
26		2	Pmc	Pcm
27		3	Pcc	—
28		4	Pma	Pbm
29		5	Pca	Pbc
30		6	Pnc	Pcn
31		7	Pmn	Pnm
32		8	Pba	—
33		9	Pna	Pbn
34		10	Pnn	—
35		11	Cmm	—
36		12	Cmc	Ccm
37		13	Ccc	—
38		14	Amm	Bmm
39		15	Abm	Bma
40		16	Ama	Bbm
41		17	Aba	Bba

Space Group Number	Class No. Schoenflies Symbol	Schoenflies Number	Mauguin symbol	
			Normal orientation	Other orientations
42		18	Fmm	—
43		19	Fdd	—
44		20	Imm	—
45		21	Iba	—
46		22	Ima	Ibm
47	8–D2h	1	Pmmm	—
48		2	Pnnn	—
49		3	Pccm	Pbmb, Pmaa
50		4	Pban	Pcna, Pncb
51		5	Pmma	Pmmb, Pmam, Pmcm, Pbmm Pcmm
52		6	Pnna	Pnnb, Pnan, Pncn, Pbnn Pcnn
53		7	Pmna	Pnmb, Pman, Pncm, Pbmn Pcnm
54		8	Pcca	Pccb, Pbab, Pbcb, Pbaa Pcaa
55		9	Pbam	Pcma, Pmcb
56		10	Pccn	Pbnb, Pnaa
57		11	Pbcm	Pbma, Pcam, Pcmb, Pmab Pmca
58		12	Pnnm	Pnmn, Pmnn
59		13	Pmmn	Pmnm, Pnmm
60		14	Pbcn	Pbna, Pcan, Pcnb, Pnab Pnca
61		15	Pbca	Pcab
62		16	Pnma	Pnam, Pbnm, Pcmn, Pmnb Pmcn
63		17	Cmcm	Ccmm, Amma, Amam, Bmmb Bbmm
64		18	Cmca	Ccma, Abma, Abam, Bmab Bbam
65		19	Cmmm	Ammm, Bmmm
66		20	Cccm	Amaa, Bbmb
67		21	Cmma	Abmm, Bmam
68		22	Ccca	Abaa, Bbaa
69		23	Fmmm	—
70		24	Fddd	—
71		25	Immm	—
72		26	Ibam	Ibma, Imaa
73		27	Ibca	—
74		28	Imma	Imam, Ibmm

DIMETRIC SPACE GROUPS

Space Group Number	Class Number Schoenflies Symbol	Schoenflies Number	Mauguin symbol	
			Normal orientation	Other orientation
75	9–S4	1	$P\bar{4}$	$C\bar{4}$
76		2	$I\bar{4}$	$F\bar{4}$
77	10–D2d	1	$P\bar{4}2m$	$C\bar{4}m2$
78		2	$P\bar{4}2c$	$C\bar{4}c2$
79		3	$P\bar{4}2_1m$	$C\bar{4}m2_1$
80		4	$P\bar{4}2_1c$	$C\bar{4}c2_1$
81		5	$C\bar{4}2m$	$P\bar{4}m2$
82		6	$C\bar{4}2c$	$P\bar{4}c2$
83		7	$C\bar{4}2b$	$P\bar{4}b2$
84		8	$C\bar{4}2n$	$P\bar{4}n2$
85		9	$F\bar{4}2m$	$I\bar{4}m2$
86		10	$F\bar{4}2c$	$I\bar{4}c2$
87		11	$I\bar{4}2m$	$F\bar{4}m2$
88		12	$I\bar{4}2d$	$F\bar{4}d2$
89	11–C4	1	P4	C4
90		2	$P4_1$	$C4_1$
91		3	$P4_2$	$C4_2$
92		4	$P4_3$	$C4_3$
93		5	I4	F4
94		6	$I4_1$	$F4_1$
95	12–D4	1	P42	C422
96		2	$P42_1$	$C422_1$
97		3	$P4_12$	$C4_122$
98		4	$P4_12_1$	$C4_122_1$
99		5	$P4_22$	$C4_222$
100		6	$P4_22_1$	$C4_222_1$
101		7	$P4_32$	$C4_322$
102		8	$P4_32_1$	$C4_322_1$
103		9	I42	F42
104		10	$I4_12$	$F4_12$
105	13–C4h	1	P4/m	C4/m
106		2	$P4_2/m$	$C4_2/m$
107		3	P4/n	C4/a
108		4	$P4_2/n$	$C4_2/a$
109		5	I4/m	F4/m
110		6	$I4_1/a$	$F4_2/d$

TABLE 3.—THE 230 SPACE GROUPS (first part)

DIMETRIC SPACE GROUPS (concl.)

Space Group Number	Class No. Schoenflies Symbol	Schoenflies Number	Mauguin symbol	
			Normal orientation	Other orientation
111	14–C4v	1	P4mm	C4mm
112		2	P4bm	C4mb
113		3	P4cm	C4mc
114		4	P4nm	C4mn
115		5	P4nc	C4cn
116		6	P4cc	C4cc
117		7	P4mc	C4cm
118		8	P4bc	C4cb
119		9	I4mm	F4mm
120		10	I4cm	F4mc
121		11	I4md	F4dm
122		12	I4cd	F4dc
123	15–D4h	1	P4/mmm	C4/mmm
124		2	P4/mcc	C4/mcc
125		3	P4/nbm	C4/amb
126		4	P4/nnc	C4/acn
127		5	P4/mbm	C4/mmb
128		6	P4/mnc	C4/mcn
129		7	P4/nmm	C4/amm
130		8	P4/ncc	C4/acc
131		9	P4/mmc	C4/mcm
132		10	P4/mcm	C4/mmc
133		11	P4/nbc	C4/acb
134		12	P4/nnm	C4/amn
135		13	P4/mbc	C4/mcb
136		14	P4/mnm	C4/mmn
137		15	P4/nmc	C4/acm
138		16	P4/ncm	C4/amc
139		17	I4/mmm	F4/mmm
140		18	I4/mcm	F4/mmc
141		19	I4/amd	F4/ddm
142		20	I4/acd	F4/ddc
143	16–C3	1	C3	H3
144		2	$C3_1$	$H3_1$
145		3	$C3_2$	$H3_2$
146		4	R3	—
147	17–D3	1	H32	C312
148		2	C32	H312
149		3	$H3_12$	$C3_112$
150		4	$C3_12$	$H3_112$
151		5	$H3_22$	$C3_212$
152		6	$C3_22$	$H3_212$
153		7	R32	—†

Space Group Number	Class No. Schoenflies Symbol	Schoenflies Number	Mauguin symbol	
			Normal orientation	Other orientation
154	18–C3v	1	C3m	H31m
155		2	H3m	C31m
156		3	C3c	H31c
157		4	H3c	C31c
158		5	R3m	—
159		6	R3c	—
160	19–C3i	1	$C\bar{3}$	$H\bar{3}$
161		2	$R\bar{3}$	—
162	20–D3d	1	$H\bar{3}m$	$C\bar{3}1m$
163		2	$H\bar{3}c$	$C\bar{3}1c$
164		3	$C\bar{3}m$	$H\bar{3}1m$
165		4	$C\bar{3}c$	$H\bar{3}1c$
166		5	$R\bar{3}m$	—
167		6	$R\bar{3}c$	—
168	21–C3h	1	$C\bar{6}$	$H\bar{6}$
169	22–D3h	1	$C\bar{6}m$	$H\bar{6}2m$
170		2	$C\bar{6}c$	$H\bar{6}2c$
171		3	$H\bar{6}m$	$C\bar{6}2m$
172		4	$H\bar{6}c$	$C\bar{6}2c$
173	23–C6	1	C6	H6
174		2	$C6_1$	$H6_1$
175		3	$C6_5$	$H6_5$
176		4	$C6_2$	$H6_2$
177		5	$C6_4$	$H6_4$
178		6	$C6_3$	$H6_3$
179	24–D6	1	C62	H62
180		2	$C6_12$	$H6_12$
181		3	$C6_52$	$H6_52$
182		4	$C6_22$	$H6_22$
183		5	$C6_42$	$H6_42$
184		6	$C6_32$	$H6_32$
185	25–C6h	1	C6/m	H6/m
186		2	$C6_3/m$	$H6_3/m$
187	26–C6v	1	C6mm	H6mm
188		2	C6cc	H6cc
189		3	C6cm	H6mc
190		4	C6mc	H6cm
191	27–D6h	1	C6/mmm	H6/mmm
192		2	C6/mcc	H6/mcc
193		3	C6/mcm	H6/mmc
194		4	C6/mmc	H6/mcm

ISOMETRIC SPACE GROUPS

Space Group Number	Class Number Schoenflies Symbol	Schoenflies Number	Mauguin symbol
195	28–T	1	P23
196		2	F23
197		3	I23
198		4	$P2_13$
199		5	$I2_13$
200	29–Th	1	Pm3
201		2	Pn3
202		3	Fm3
203		4	Fd3
204		5	Im3
205		6	Pa3
206		7	Ia3
207	30–Td	1	$P\bar{4}3m$
208		2	$F\bar{4}3m$
209		3	$I\bar{4}3m$
210		4	$P\bar{4}3n$
211		5	$F\bar{4}3c$
212		6	$I\bar{4}3d$
213	31–O	1	P43
214		2	$P4_23$
215		3	F43
216		4	$F4_13$
217		5	I43
218		6	$P4_13$
219		7	$P4_33$
220		8	$I4_13$
221	32–Oh	1	Pm3m
222		2	Pn3n
223		3	Pm3n
224		4	Pn3m
225		5	Fm3m
226		6	Fm3c
227		7	Fd3m
228		8	Fd3c
229		9	Im3m
230		10	Ia3d

TABLE 3.—THE 230 SPACE GROUPS (second part)

Table 3 showing the 230 space groups is taken from Bernal et al (1, 525–530), rearranged in sequence to conform to the development of the crystal classes as shown in Fig. 1. In the Mauguin space group symbolism the initial capital letter shows the space lattice according to the terminology of Table 2. The other symbols correspond to the Mauguin point-group symbols as shown in Fig. 1 (lower right) with the addition of screw axes (shown by a numerical subscript to the axis symbol, with different subscript numbers for different types of screw axes) and glide planes. For the latter the letters a, b, c are used if the translation is $\frac{a}{2}$, $\frac{b}{2}$, $\frac{c}{2}$; n is used if the translation is $\frac{a+b}{2}$, $\frac{b+c}{2}$ or $\frac{a+c}{2}$, or from the corner to the center of a face parallel the glide plane; and d where it is $\frac{a+b}{4}$, $\frac{b+c}{4}$, or $\frac{a+c}{4}$, or one-quarter of a face-diagonal. From the Mauguin symbol of any one of the 230 space groups, the corresponding point group (crystal class) can be obtained by dropping the space lattice designation and the subscript numeral indicating a screw axis and substituting m for any of the letters indicating a glide plane.

CONCLUDING REMARKS

Scientists should make classifications their slaves, not the reverse. One[22] would have the systems as more fundamental than the classes, while others (10, 199 and 12, 383) hold out for the opposite. Much depends on the purposes to which a classification is to be put. The optical crystallographer is satisfied with the three divisions, as is the crystallographer working in many other physical fields. The working mineralogist rarely uses more than systematic splitting as an aid in non-instrumental mineral determination. The pure morphologist may find use for the 32 classes, but this is not universally true. The crystal structure worker needs the 230 space groups. Numerous other types of groupings have been proposed, as examination of the very limited bibliography here appended will prove. Swartz (12, 385–397) has published a very satisfactory brief history of the subject up to 1902, well worthy of perusal by the present-day student.

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[22] *Am. Mineral.*, vol. **16**, pp. 26, 30, 1931.

The 32 classes may be developed using as symmetry operations only rotations, inversions, and the two combined (rotary inversions); or rotations, reflections, and the two combined (rotary reflections) will lead to their derivation.[23] Normally different types of classification will come from the two methods, as is demonstrated by numerous papers. Fig. 1 presents a classification which depends less upon the type of symmetry operation used to develop the classes than it does on the order of increasing inherent symmetry as one proceeds from class to class. While the term "anastrephaxial" implies that inversion axes are stressed, this is hardly true as comparison with Wyckoff (17, 15) will show. The term as well as one set of symbols conforms to those of Mauguin; the Schoenflies symbols including those of the alternating axes (Sn) are also given; no matter which are used the same results are reached in this type of classification.

So far as known the class numbers of Fig. 1 do not agree in all details with those of any other author. History indicates that the numbers here given will not meet with universal approval. The numbering of the space groups up to 230 as is done in Table 3 can have no greater significance than do the class numbers themselves. Unless general agreement can be reached on class number—as has been done on the numbering of space groups in any one class—names or symbols are to be preferred. In any case practically the only advantage of numbers is in ease of printing. The tremendous advantages in all other ways of the Mauguin space group symbolism, which in place of a numeral of no inherent significance puts a simple set of symbols giving the essential symmetry elements of the space group in question, and the extreme ease with which the corresponding point group symbol can be derived from this, warrants the rapid adoption of this system.

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[23] Failure to recognize this accounts for such statements as "the center of symmetry . . . is manifestly secondary" (12, 384–385), "the center of symmetry is a true (i.e., essential?—D.J.F.) element of symmetry" (10, 166), "both rotatory-inversions and rotatory-reflections must be used as symmetry operations" (10, 201), and "only two-, four-, and six-fold rotary reflection axes are possible" (Sol!er, *op. it.*, p. 418).

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SYMMETRY SYSTEM	Principal Axis	AXIAL = SYMMETRY AXES ONLY			AXIHEDRAL = BOTH AXES AND PLANES				Row number	SYMMETRY SYSTEM
		MONAXIAL One (polar) axis only Hemimorphic Cyclic = Cn	POLYAXIAL More than one axis—no planes Enantiomorphic Dihedral = Dn	ANASTREPH-AXIAL One inversion axis only Sphenoidal = Sn	ORTHAXI-HEDRAL One plane (horizontal) perpendicular to one axis. C_n^h	MONAXI-HEDRAL One (polar) axis only, with parallel (vertical) planes. Hemimorphic C_n^v	MESAXI-HEDRAL Planes (none horizontal) between (diagonal to) axes. D_n^d	POLYAXI-HEDRAL Planes (one horizontal) coinciding with symmetry axes. D_n^h		
TRIMETRIC DIVISION										
TRICLINIC	1 $\bar{1}$	1(XXXII) C_1 Asymmetric 1	(Cf. 4)	2(XXXI) $C_i(=S_2)$ Pinacoidal $\bar{1}(=i)$	(Cf. 3)		(Cf. 5)	(Cf. 7)	1 2	TRICLINIC
MONOCLINIC	$\bar{2}$			3(XXX) $C_s(=S)$** Clinohedral $m(=\bar{2})$					3	MONOCLINIC
	2	4(XXIX) C_2 Sphenoidal 2			5(XXVIII) C_{2h}* Prismatic 2/m (i)				4	
ORTHO-RHOMBIC	2		6(XXVII) $D_2(=V)$ Orthorhombic Disphenoidal 222			7(XXVI) C_{2v} Orthorhombic Pyramidal m m (2 m m)		8(XXV) $D_{2h}(=V_h)$ Orthorhombic Dipyramidal mmm (2/m2/m2/m i)	5	ORTHO-RHOMBIC
DIMETRIC DIVISION										
TETRAG-ONAL	$\bar{4}$			9(XXIV) $S_4(=C'_4)$ Tetragonal Disphenoidal $\bar{4}$			10(XXIII) $D_{2d}(=V_d)$ Ditetragonal Scalenohedral $\bar{4}$ 2 m($\bar{4}$ 2^2 m^2)		6	TETRAG-ONAL
	4	11(XXII) C_4 Tetragonal Pyramidal 4	12(XXI) D_4 Tetragonal Trapezohedral 4 2(4 2^2 2^2)		13(XX) C_{4h} Tetragonal Dipyramidal 4/m (i)	14(XIX) C_{4v} Ditetragonal Pyramidal 4 m m(4 m^2 m^2)		15(XVIII) D_{4h} Ditetragonal Dipyramidal 4/mmm(4/m2/$m^2$2/m^2i)	7	
HEXAGONAL Rhombohedral Subsystem	3	16(XVII) C_3 Trigonal Pyramidal 3	17(XVI) D_3 Trigonal Trapezohedral 3 2(3 2^3)			18(XV) C_{3v} Ditrigonal Pyramidal 3 m(3 m^3)			8	Rhombohedral Subsystem HEXAGONAL
	$\bar{3}$			19(XIV) $C_{3i}(=S_6)$ Trigonal Rhombohedral $\bar{3}$ (i)			20(XIII) D_{3d} Ditrigonal Scalenohedral $\bar{3}$ m($\bar{3}$ 2/m^3 i)		9	
Hexagonal Subsystem	$\bar{6}$			21(XII) $C_{3h}(=S_3)$ Trigonal Dipyramidal $\bar{6}$ (=3/m)				22(XI) D_{3h} Ditrigonal Dipyramidal $\bar{6}$ m(3/m[=$\bar{6}$]$2^3$$m^3$)	10	Hexagonal Subsystem
	6	23(X) C_6 Hexagonal Pyramidal 6	24(IX) D_6 Hexagonal Trapezohedral 6 2(6 2^3 2^3)		25(VIII) C_{6h} Hexagonal Dipyramidal 6/m (i)	26(VII) C_{6v} Dihexagonal Pyramidal 6 m m(6 m^3 m^3)		27(VI) D_{6h} Dihexagonal Dipyramidal 6/mmm(6/m2/$m^3$2/m^3i)	11	
MONOMETRIC DIVISION										
ISOMETRIC	2^3		28(V) T Gyrotris-tetrahedral 2 3(2^3 3^4)					29(IV) T_h Diploidal m 3(2/m^3 $\bar{3}^4$ i)	12	ISOMETRIC
	$\bar{4}^3$						30(III) T_d Hextetrahedral $\bar{4}$ 3 m($\bar{4}^3$ 3^4 m^6)		13	
	4^3		31(II) O Gyricosi-tetrahedral 4 3(4^3 3^4 2^6)					32(I) O_h Hexoctahedral m 3 m(4/$m^3$$\bar{3}^4$2/$m^6$ i)	14	
Column Number		I	II	III	IV	V	VI	VII		Column number

EXPLANATION: Significance of position is indicated in the rectangle to the left. The class number in the upper left is shown in Arabic numerals going from minimum to maximum symmetry, and in Roman numerals for the reverse. The Schoenflies symbol is used in the upper right. With few exceptions the class name is according to Groth (but using Greek prefixes). Symbol and total symmetry are shown below with Hermann-Mauguin symbols; these are explained in the other column

number symbol
class
name
symbol (symmetry)

REMARKS: Crystals of classes in the monaxial and monaxihedral families, as well as those of classes 3, 17, 22, 28, and 30, may show pyro- and piezo-electric phenomena. Rotatory polarization may occur in monaxial and polyaxial crystals.

Hermann-Mauguin symbols:
- 1, 2, 3, 4, 6,—(ordinary) symmetry axes.
- $\bar{1}(=i)$, $\bar{2}(=m)$, $\bar{3}$, $\bar{4}$, $\bar{6}(=3/m)$,—inversion axes.
- $m(=\bar{2})$—plane of symmetry, $i(=\bar{1})$—center of symmetry (inversion).
- 2/m, $3/m(=\bar{6})$, 4/m, 6/m,—axes with normal plane of symmetry.

Superscripts indicate more than one of a given element of symmetry.

FOOTNOTES:

* In the monoclinic morphologists generally make the symmetry axis = b; thus the Schoenflies symbol for Class 5 may not seem appropriate,** nor would the symbol C_{1h} which has been used for Class 3.

In Classes 6, 8, and 10, Q (quadratic) may replace V (vierer).

Fig. 1.—CRYSTAL CLASSES (point groups) arranged by D. Jerome Fisher.

NOTES AND NEWS

AMPHIBOLE FROM THE PURCELL SILLS, BRITISH COLUMBIA[1]

H. M. A. RICE.[2]

A great band of pre-Cambrian (Beltian) sediments, 30,000 feet or more thick, is exposed in the southeast corner of British Columbia. During late Beltian time these sediments were intruded by the Purcell sills and associated dykes.[3]

The Purcell sills vary in size from thin sheets of limited extent to huge bodies over a thousand feet thick and many miles long. The normal rock is a fine to medium grained diorite in which lath-shaped amphiboles appear conspicuously in a confused aggregate of plagioclase and accessory minerals. It has approximately the following average mineralogical composition:

Plagioclase	40%
Amphibole	50
Quartz	4
Ilmenite and magnetite	2
Other accessories	4
	100%

Amphibole is the most abundant constituent and, in certain phases, forms over 70 per cent of the rock. It varies considerably in grain size, but frequently develops as plume-shaped crystals one to two inches long. As a preliminary examination showed it to differ considerably from any amphibole described in the literature, its optical properties were carefully determined in thin sections and by the oil immersion method as outlined by Larsen,[4] and two partial chemical analyses were made.

The amphibole was found to be of two different types designated as "A" and "B," both of which never occur in the same sill.

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[1] Published by permission of the Director of the Geological Survey of Canada.

[2] Balch Graduate School of the Geological Sciences, California Institute of Technology, Pasadena, California. Contribution No. 141.

[3] Daly, R. A., North American Cordillera, 49th Parallel: *Geol. Sur. Can.*, Mem. **38,** 1913.

Schofield, S. J., Geology of the Cranbrook Map Area, B.C.: *Geol. Sur. Can.*, Mem. **76,** 1915.

Rice, H. M. A., Geology of the Cranbrook District, British Columbia: Unpublished Thesis, Calif. Inst. of Tech., 1934.

[4] Larsen, Esper S., The Microscopic Determination of the Non-Opaque Minerals: *U. S. Geol. Sur.*, Bull. **679,** 1921.

The optical and chemical properties are given in the following tables:

CHEMICAL ANALYSES[5]

	Type "A"	Type "B"
SiO_2	42.80%	44.66%
Al_2O_3	11.26	12.64
Fe_2O_3	15.06	15.13
FeO	14.21	8.85
MgO	3.82	4.85
CaO	10.08	10.70
Na_2O and K_2O	1.92	1.80
H_2O at 100°C.	0.16	0.15
H_2O at 300°C.	0.38	0.35
	99.69	99.13

The deficiency shown in both analyses is represented in part by manganese which, although not determined, is present in both types of amphibole.

OPTICAL PROPERTIES

Type "A"

	α	β	γ	$\gamma-\alpha$	$Z\wedge C$	Calculated 2V Sign
1. At base of sill.	1.661	1.674	1.676	.015	15°	43° neg.
115′ from base.	1.662	1.679	1.684	.022	18°	57° "
Close to top.	1.666	1.678	1.688	.024	18°	84° "
2. Coarse-grained sill.	1.658	1.679	1.682	.024	17°	41° "
3. 61′ from base.	1.660	1.677	1.681	.021	17°	51° "
114′ from base.	1.660	1.678	1.683	.023	17°	55° "
4. From ore.	1.659	1.675	1.678	.019	17°	46° "
Average Type "A"	1.661	1.677	1.682	.021	17°	58° "

Type "B"

	α	β	γ	$\gamma-\alpha$	$Z\wedge C$	Calculated 2V Sign
5. Center of Sill.	1.644	1.656	1.663	.019	18°	76° neg.
Near top.	1.638	1.654	1.658	.020	18°	53° "
6. Large sill.	1.641	1.660	1.666	.025	19°	58° "
Average Type "B"	1.641	1.657	1.662	.021	18°	58° "

1. Sill about 225 feet thick near road four miles southwest of Cranbrook.
2. Sill crossing road two miles south of Aldridge.
3. Upper sill, about 200 feet thick, exposed in bluff northeast of Lumberton.
4. "Differentiate" ore from the Mystery Mine, Alki Creek, above St. Mary's Lake.
5. Lower sill exposed in bluff northeast of Lumberton.
6. Large sill from top of butte southeast of Sullivan concentrator.

[5] Ed Eisenhauer, analyst.

Pleochroism

	Type "A"	Type "B"
X	Pale yellow	Pale yellow
Y	Olive green	Olive green
Z	Greenish blue	Greenish blue

Absorption

Type "A"	Type "B"
$Y>Z>X$	$Y>Z>X$

Both types resemble common hornblende, but have a higher iron content, a smaller extinction angle, a different pleochroism, and "B" lower indices of refraction. It is noteworthy that the relations $Fe_2O_3>FeO>Al_2O_3$ (Type "A") and $Fe_2O_3>Al_2O_3>FeO$ (Type "B") are of rare occurrence in amphiboles of the hornblende group and have been reported only from alkaline rocks. In this case being described the rock is a normal diorite.

No varieties intermediate between the two types are known. "A" occurs in the sills in association with plagioclase varying from oligoclase to acid andesine (Ab 88 per cent to Ab 60 per cent), while "B" is found with plagioclase varying from basic andesine to acid labradorite (Ab 54 per cent to Ab 46 per cent).

In some of the Purcell sills small ore deposits occur composed almost entirely of chalcopyrite and pyrrhotite with amphibole as the only important gangue mineral. This amphibole is identical with type "A." The abundance of this mineral in the ore, its similarity with a primary constituent of the sills, and the fact that it is, in part at least, clearly cutting the sulphides suggest a close relationship between the ore and the sills.

ACKNOWLEDGMENTS

The writer wishes to express his indebtedness to Dr. Ian Campbell and Dr. René Engel for help and advice in securing the data on the amphibole and in the preparation of this paper.

OPTICALLY POSITIVE CORDIERITE FROM NEW HAMPSHIRE

L. C. Conant, *Cornell University, Ithaca, N. Y.*

While making a study of the garnet deposits of New Hampshire, granite specimens were collected from fresh road cuts for state highway No. 9 in the town of Stoddard, Cheshire County, about 2½ miles west of the Antrim town line (Lovewell Mountain Quadrangle). Microscopic study of this granite led to the discovery of optically positive cordierite. Since anomalous cordierite has been reported only from India[1] and the Northwest Territories,[2] it is deemed worth while to note this occurrence.

The cordierite is found in a conspicuously porphyritic granite, Meridith granite of Billings,[3] which occurs as a batholith. This granite is characterized by the presence of abundant orthoclase phenocrysts 2 to 4 inches long, twinned according to the Carlsbad law, and embedded in a matrix consisting chiefly of andesine feldspar, quartz, biotite, microcline, and scattered garnets about a quarter of an inch in diameter. For two or three miles along highway No. 9 there are numerous fresh exposures of the porphyritic granite containing scattered inclusions. Several phases of the granite are exposed, some of which have probably resulted from the assimilation of roof material. Certain of these phases contain inconspicuous grains of cordierite in which the typical blue color is poorly developed. Only careful inspection of the granite specimen enables one to see the somewhat smoky and very slightly bluish grains of the mineral. The cordierite is most abundant in certain dark crystalline patches containing sillimanite, and in a curious mottled salmon-colored variety of the granite, the color of which is due largely to the presence of garnet.

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[1] Chacko, I. C., Optically Positive Cordierite: *Geol. Mag.*, vol. **3,** pp. 462–474, 1916; *Min. Abst.*, vol. **1,** pp. 66–67, 1920.

Krishnan, M. S., Note on Cordierite in a Cordierite Gneiss from Madura District, Madras, India: *Mineral. Mag.*, vol. **20,** pp. 248–251, 1924.

Iyer, L. A. N., A Study of the Calc-Gneisses, Scapolite Gneisses, and Cordierite-Garnet-Sillimanite-Rocks of Coimbatore, Madras Presidency; with Comparisons to Other Similar Occurrences in India: *Mineral. Mag.*, vol. **22,** pp. 121–135, 1929.

[2] Rutherford, R. L., Optically Positive Cordierite from the Northwest Territories, Canada: *Am. Mineral.* vol. **18,** p. 216, 1933.

[3] Billings, Marland, The Petrology of the North Conway Quadrangle in the White Mountains of New Hampshire: *Proc. Am. Acad. Arts and Sciences*, vol. **63,** No. 3, p. 83, May 1928.

That the mineral is cordierite, in spite of its positive character is indicated by the following facts:

(1) Typical golden-yellow halos surround included zircons;

(2) Characteristic polysynthetic and cyclic twinning can be seen in many of the grains;

(3) Alteration to pinite has proceeded in customary manner along irregular lines.

The material at hand has not lent itself to separation for a chemical analysis, but it is hoped to obtain later some specimens which will be suitable for this purpose, and to publish the results.

NOTE ON THE OCCURRENCE OF VIVIANITE IN THE DISTRICT OF COLUMBIA

JAMES H. BENN,* *U. S. National Museum.*

During the excavations for the numerous governmental buildings along Constitution Avenue in the city of Washington, it was called to the attention of the writer that small masses of a blue powderlike mineral were being found embedded in the clay. Mr. Vincent Tilton of Washington first observed the mineral which was being taken from the site upon which now stands the building of the United States Department of Commerce. Later Dr. R. W. Brown of the United States Geological Survey submitted samples procured from the excavation upon which rests the new Archives Building.

On close examination the blue masses were found to be the ferrous phosphate, vivianite, which so far as is known, has not been recorded from the District of Columbia.

In form, the masses appear as small globular nodules, ranging in size from a millimeter to a centimeter; the larger being less numerous. Some of those obtained from the Commerce building site were elongated to above three centimeters and had a somewhat rootlike shape.

The structure of the viviante ranges from a smooth powder in the smaller nodules to a very fine granular condition in those of greater size; and in color varies from medium blue to deep blue.

In occurrence the mineral is found embedded some twenty to thirty feet below the surface. It is associated with limonite disseminated in surficial deposits of sandy-clay; and with flecks of mica (muscovite) which has been derived from the weathering of the Piedmont schist and gneiss.

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* Published by permission of the Secretary of the Smithsonian Institution.

Vivianite in the surrounding regions has been reported from the northern part of Somerset and Worcester Counties in Maryland, where it was also found associated with limonite.

In Virginia, this mineral has been recorded from Stafford County occurring with bog iron ore; and at Falmouth (in the same county) has been found associated with gold and galena.

The excavations along Constitution Avenue where the District specimens were secured, follow the line of a canal which was covered over many years ago. Throughout this region, the rocks are the results of a reclaimed tide marsh, resting upon the Pleistocene loam and gravel of the latest Columbian terrace. It would seem that with the abundance of plants and other organic bodies which must have existed along the old canal, and the presence of iron and water in the soil of the reclaimed area, the remains of such organic bodies have been replaced by the ferrous phosphate.

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY

Academy of Natural Sciences, Philadelphia, Pa., December 6th, 1934.

Vice-President H. W. Arndt presided at a stated meeting of the Philadelphia Mineralogical Society, 42 members and 33 visitors being present.

Rev. Bentley R. Morrison spoke on "Labrador: Geology and Minerals." The talk was illustrated with maps, specimens, and hunting equipment and clothing worn by the eskimos.

Rev. Morrison and a party of seven went to Labrador during the summer of 1934 to quarry labradorite under the auspices of the International Grenfell Association. Permit to quarry had to be obtained at St. Johns and claims must be worked a minimum of 160 days in four years.

The scene of the quarrying operations was one of the long bays known as the Bay of Nain. The quarry was about 50 feet long and seemed to represent a concentration of labradorite of the quality which could be used in jewelry and for ornamental purposes. The foot wall is a trap rock. The whole 600 ft. hill in which the quarry was located is anorthosite. At the northern end of the hill, 500 lbs. of pure hypersthene was found. The quarry operations resulted in some 200 tons of the labradorite being removed which was sorted to 50 tons of usable material.

W. H. Flack, *Secretary*

Academy of Natural Sciences, Philadelphia, Pa., Jan. 3, 1935.

President Gillson called to order a stated meeting of the Philadelphia Mineralogical Society, 43 members and 23 visitors being present.

Louis Moyd reported obtaining datolite, amethyst and quartz pseudomorphs after anhydrite at the Prospect Park Quarry, N.J. Chas. R. Toothaker exhibited tribo-luminescent sphalerite from the Horn Silver Mine, Tintic District, Utah. Albert Jehle exhibited limonite pseudomorphs after pyrite crystals from Oreland, Pa., and black tourmaline crystals from the Henry Avenue bridge over the Wissahickon Creek, Philadelphia. Harold Poole exhibited sphalerite from the Henry Avenue bridge, Philadelphia.

Prof. A. F. Buddington of Princeton University spoke on the "Classification of Mineral Associations and Geologic Thermometry." Minerals are sensitive to variations in temperature; quartz at 575° changes from low to high temperature quartz, and green hornblende changes to brown hornblende at 800°. In the Alaskan coast range batholith, 1000 miles long and 35 to 100 miles wide, chemical composition remains the same, but there are totally different mineral associations presumably from changes in temperature.

The talk was illustrated with specimens and blackboard diagrams and the Society gave Dr. Buddington a rising vote of thanks for his excellent presentation.

W. H. Flack, *Secretary*

MINERALOGICAL SOCIETY OF GREAT BRITAIN AND IRELAND

Mineralogical Society, January 24, 1935.

The following papers were read:—

(1) Notes on the occurrence of fluorite in Aberdeenshire and Banffshire. By Mr. Arthur Russell.

Crystallized fluorite, varying in color from nearly colorless to yellow, violet, and green, has been collected recently by the author from Abergairn Lead mine, Ballater; Creag an t-Seabhaig, on the north side of the Pass of Ballater; and Na Tri Chaochain, River Avon, between Tomintoul and Inchrory, Banffshire. The fluorite and associated minerals are described.

(2) On the occurrence of chondrodite in the Glenelg Limestone of Inverness-shire. By Prof. H. H. Read and Mr. I. S. Double.

Small grains of chondrodite have been identified in forsterite-marbles from several localities in the Glenelg district. Its most common mode of occurrence is as small granules forming rims round crystals of forsterite, and it is suggested that the chondrodite has been formed from forsterite by the accession of fluorine- and hydroxyl-bearing fluids. Previous records of chondrodite in the British Isles have not been confirmed by recent work.

(3) Ankerites of the Northumberland coalfield. By Dr. L. Hawkes and Dr. J. A. Smythe.

Ankerite and ankeritic calcite are described from veins in the Coal Measures on the coast at Hartley, and from various seams in the Northumberland Coal field. Evidence is given that, in the portion of the coal-field examined, both minerals are of constant composition, and that the deposition of the ankerite preceded that of the calcite. The ankerites are members of an isomorphous series consisting of dolomite $MgCO_3 \cdot CaCO_3$, and ferro-dolomite $FeCO_3$ $CaCO_3$, with small amounts of mangan-dolomite $MnCO_3 \cdot CaCO_3$, and they may hold up to 20% of $CaCO_3$ in solid solution.

(4) Apophyllite from Traprain Law, East Lothian. By Mr. J. G. C. Anderson and Mr. S. Elder.

Well-crystallized apophyllite is described from druses in phonolite. The apophyllite is associated with analcime and pectolite. Other localities for apophyllite in Scotland are mentioned.

(5) Studies on the Zeolites, Part IX. Scolecite and Metascolecite. By Mr. M. H. Hey.

Results of x-ray, goniometric and optical studies on analysed specimens of scolecite and of base exchange experiments are given. Vapour pressure work clearly shows that the water is divided into a more volatile group of 16 and a less volatile group of 8 mols. per unit cell. Before the whole of the first 8 of the more volatile water molecules have been expelled, transition occurs to metascolecite.

(6) A new apparatus for the determination of carbon dioxide. By Mr. H. H. Hey.

A simple apparatus is described for the collection of carbon dioxide in baryta solution, and the subsequent filtration and washing of the barium carbonate produced with complete exclusion of atmospheric carbon dioxide.

NEW MINERAL NAMES

Janite

Thugutt, Stanisaw Józef: O janicie, nowym minerale z Janowej Doliny na Wołyniu (Janite, a new mineral from Janowa Dolina in Volhynia). *Arch. Mineral.* Warsaw, vol. 9, pp. 93–98, 1933. Polish with French summary.

Name: From the locality, Janowa Dolina.

Chemical Properties: A hydrous silicate of aluminum, iron, calcium, magnesium, etc. $(R_2O, RO)\ R_2O_3 \cdot 5SiO_2 \cdot 5\ H_2O$; (approx.) Analysis: SiO_2 49.67

Al_2O_3 7.58, Fe_2O_3 15.67, MnO 0.85, CaO 3.33, MgO 3.25, K_2O 0.92, Na_2O 1.46, H_2O 16.57; sum 99.30. Insoluble in hydrochloric and sulfuric acids.

Physical and Optical Properties: Color dark red. G. 2.32. Soft to the touch. Optically negative. $1.527 > n > 1.516$. Birefringence feeble. Not pleochroic. Extinction parallel. Cleavage basal, pronounced.

Occurrence: Found in a plagioclase-pyroxene rock with secondary quartz, chalcedony, opal, chlorite and iron oxides in segmental spherulites of plates.

W. F. Foshag

Sahlinite

Aminoff, G.: Note on a new Mineral from Långban (Sahlinite). *Geol. Fören. Förhandl.*, Stockholm, vol. **56**, pp. 493–4, 1934.

Name: In honor of Dr. Carl Sahlin.

Chemical Properties: A basic chlor-arsenate of lead, $12PbO \cdot As_2O_5 \cdot 2PbCl_2$. Analysis: (by R. Blix) PbO 89.33, As_2O_5 6.57, CaO 0.46, CO_2 0.43, Cl_2 4.05, H_2O 0.10; sum 100.94, $(-O = Cl_2\ 0.91) = 100.03$.

Crystallographical Properties: Monoclinic, cleavage parallel to plane of symmetry, prominent.

Physical and Optical Properties: Color sulfur yellow. Hd. 2–3, G. 7.95. Biaxial, negative. Bx_a is normal to (010). $2E = 96°38'$. n high.

Occurrence: As aggregates of thin scales with hausmannite in dolomite.

W. F. F.

Kiscellite

L. Zechmeister, G. Tóth and A. Koch: Untersuchung eines neuen fossilen Harzes: Kiscellit. (Investigation of a new fossil resin: Kiscellite). *Centr. Min. Geol.*, Abt. **A**, No. 2, pp. 60–61, 1934.

Name: From the name—Kiscellar Tegel (formation) of Budapest.

Chemical Properties: A sulfur bearing hydrocarbon resin (without oxygen). Analysis: C 84.47, H 11.12, S 3.99, Ash 0.31; sum 99.89. Difficulty soluble. *m, p.* not sharp. Upon heating evolves H_2S. Ignited burns with a smoky flame with a resinous, aromatic odor.

Physical Properties: Color on surface brown, interior olive green in spots. Streak pale yellow. Transparent in splinters. $n_D = 1.5418$ (20°). G. = 1.186 (20°). Resembles amber, ajkaite and telegdite.

Occurrence: From a sandy layer in the littoral formations of the kiscellar Tegel (Middle Oligocene) formation. Plant remains including conifers, are found in this formation.

W. F. F.

Pseudosillimanite

Jacques de Lapparent: Conglomérats et Phtanites des Terrains Dévoniens de la Vallèe de la Bruche (Vosges d'Alsace). *Compt. Rend. Congrès Soc. Savantes Sci. Paris*, **1920**, pp. 73–77.

In a black aphanitic rock in the conglomerates of Hersback occurs small needle like crystals with lozenge shaped cross section with strong refringence (less than epidote), strong birefringence and positive elongation. The plane of the optic axes lies across one diagonal and the obtuse bisectrix is perpendicular to the elongation. 2V is not large. From its resemblance to sillimanite it is called pseudo-sillimanite.

W. F. F.

Lusakite

A. C. Skerl, F. A. Bannister and A. W. Groves: Lusakite, a cobalt-bearing silicate from Northern Rhodesia. *Mineral. Mag.*, vol. **23**, no. 146, pp. 598–606, 1934.

Name: From the locality Lusaka, Northern Rhodesia.

Chemical Composition: A silicate of iron, aluminum, cobalt and magnesia: $H_2O.4R''O.9Al_2O_3.8\ SiO_2(R''=Co.Mg.Fe)$ Analysis no. 1 (not quite pure); SiO_2 27.07, TiO_2 0.80, Al_2O_3 48.15, Cr_2O_3 trace, Fe_2O_3 10.83, FeO 2.22, NiO 0.53, CoO 6.79, MnO trace, MgO 2.44, CaO nil, H_2O (+110°) 1.00, H_2O (−110°) 0.35, S 0.07; total 100.25. Analysis no. 2; SiO_2 27.23, TiO_2 0.50, Al_2O_3 50.72, Cr_2O_3 n.d., Fe_2O_3 4.96, FeO 3.42, NiO 0.89, CoO 8.48, MnO 0.08, MgO 2.56, CaO nil, H_2O (+110°) 1.19, H_2O (−110°) nil; total 100.03. Insoluble in all acids including HF. B. B. infusible but yields a black bead in the electric arc.

Crystallographical Properties: Orthorhombic; habit tabular to equidimensional. Forms (010) and (110). $010\wedge 110=64°37'$. $a:b:c=0.474:1$ (Goniometric); $0.473:1:0.340$ (*x*-ray). Space group V_h^{17}. Unit cell dimensions $a=7.86$, $b=16.62$, $c=5.65$Å.

Physical and Optical Properties: Color black, small crystals deep cobalt blue by transmitted light. Streak light blue. Luster vitreous. Brittle. Fracture subconchoidal. Hd. 7–1/2. G. 3.767. Under the microscope vivid cobalt blue. Cleavage (010) distinct, (100) less so. n about 1.74. 2V large, parallel extinction. Strongly pleochroic. X=cobalt-blue, Y=violet blue, Z=violet.

Occurrence: Found in a gneissoid rock intimately associated with quartz, cyanite and magnetite, about 80 miles east of Lusaka, Northern Rhodesia. Lusakite forms from 5–40% (average 30%) of the rock.

W. F. F.

Hydrocalumite

C. E. Tilley: Hydrocalumite ($4CaO.Al_2O_3.12H_2O$), a new mineral from Scawt Hill, Co. Antrim. *Mineral. Mag.*, vol. **23**, no. 146, pp. 607–615, 1934.

Name: In allusion to its composition as an hydrated calcium aluminate.

Chemical Composition: An hydrated calcium aluminate; $4CaO.Al_2O_3.12H_2O$. Analyses (by M. H. Hey): CaO 41.5, 40.0; Al_2O_3 18.8, 18.1; H_2O 38.5; CO_2 1.8; [ign. 40.3]. Soluble in weak HCl. Alkaline to litmus. In closed tube decrepitates and gives off water.

Crystallographical Properties: Monoclinic, pseudo-hexagonal. $a=9.6$ Å, $b=11.4$ Å, $c=16.84$ Å, $\beta=69°$. Space-group $P2_1$. Cleavage: basal, perfect.

Physical and Optical Properties: Colorless to light green. Luster vitreous inclining to pearly on cleavage surfaces. Biaxial negative. Cleavage fragments show emergence of acute bisectrix almost normal to cleavage. Plane of optic axis parallel to (010). $Y=b$. $\alpha=1.535$, $\beta=1.553$, $\gamma=1.557$. $2V=24°+2°$. Uniaxial at 90–95°C. Hd. 3. G. 2.15.

Occurrence: Found as infillings in larnite rock from Scawt Hill with afwillite, portlandite and ettringite.

W. F. F.

Matlockite

F. A. Bannister, (with chemical analysis by M. H. Hey). The crystal-structure and optical properties of matlockite (PbFCl). *Mineral. Mag.*, vol. **23**, no. 146, pp. 587–597, 1934.

A new analysis of matlockite from Cromford, Derbyshire, gave: Pb 79.55, F 7.11, Cl 13.44. G. = 7.05. These results confirm the suggestion of Nieuwenkamp (cf. *Am. Mineral.*, vol. **19**, p. 287, 1934) that matlockite is a lead fluochloride. *X*-ray and optical data are also given.

W. F. F.

Errata

The following corrections should be noted in the article by N. Sundius, *Am. Mineralogist*, vol. **16**, pp. 488–518, 1931: Page 505, fourth line from top, read "$\gamma-\beta=0.014$," instead of "$\beta-\alpha=0.014$." Read "$\beta=1.740$" instead of "$\beta=1.752$." Page 518, Table II, for No. 13, Sobralite, V. Silvberg (anal. 14), read under β "1.740" instead of "1.752."

BOOK REVIEW

GETTING ACQUAINTED WITH MINERALS. George Letchworth English. 324 pages with 258 illustrations. Price $2.50 net. Mineralogical Publishing Co., 50 Brighton St., Rochester, New York.

This attractive book was written primarily to create an abiding interest in minerals on the part of those beginning their study of this subject. The author, by virtue of his extensive collecting trips to all parts of the world and his life-long intimate experience in examining and evaluating mineral specimens, was unusually well qualified to undertake such a task. The logical arrangement, interesting style of presentation and numerous excellent illustrations demonstrate the success of the venture in producing a text that has unusual merit and is unique in this field. The book should appeal not only to the amateur but the more advanced student will also profit by a careful reading of its pages.

The major portion of the book consisting of 324 pages is devoted to a discussion of the physical properties and description of the more common mineral species, although rocks are also given brief consideration; tables for the megascopic determination of minerals and a pronouncing vocabulary conclude the volume.

W. F. H.

Dr. M. N. Short, Professor of Optical Mineralogy at the University of Arizona, has been appointed special lecturer in the Departments of Mineralogy and Geology at the University of Michigan during the coming Summer Session. He will conduct a laboratory course in mineralography for a limited number of graduate students with proper qualifications.